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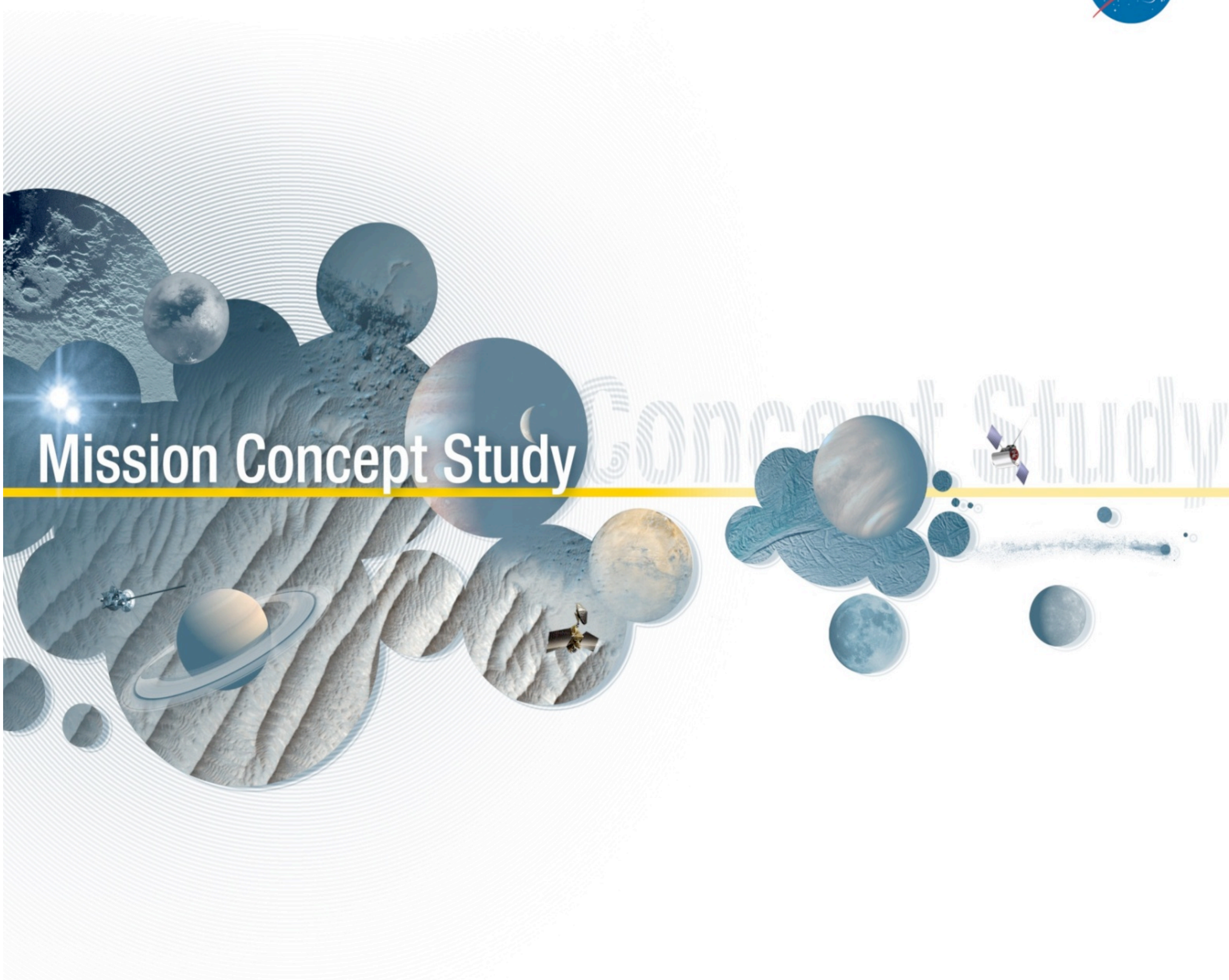

Lunar Geophysical Network (LGN)

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Planetary Science Decadal Survey

Mission Concept Study Final Report

Contents

Executive Summary

The purpose of this study was to determine the feasibility of a Lunar Geophysical Network (LGN) mission to the Moon. It was conducted by Marshall Space Flight Center's, Robotic Lunar Lander Development Project team in partnership with the Johns Hopkins University/Applied Physics Laboratory (JHU/APL). This study was documented based on previous trades, analysis, and options for concepts developed by the team over the last 18 months, with a goal of determining whether such a mission could be accomplished within a Principal Investigator (PI)-led mission cost cap (e.g. New Frontiers). The mission focuses on the scientific rationale for deploying a global, long-lived network of geophysical instruments on the surface of the Moon to understand the nature and evolution of the lunar interior from the crust to the core.

The science measurements, corresponding science instrument and their relationships to overall science goals and objectives were provided as LGN study guidelines by the Decadal Survey Inner Planets Panel. The complete set of instruments including seismometers, magnetometer, heat flow sensors, and retroreflectors, were included. A scientifically, self sufficient network would consist of a minimum of four network stations on the lunar surface operating through an entire lunar tidal cycle (six years).

This lander mission concept utilizes the Advanced Stirling Radioisotope Generator (ASRG), enabling a small, reduced-mass lander configuration with adequate power for the cruise and landing phases of mission operation, including continuous operations (day and night) on the lunar surface. The design makes use of a high-pressure, high thrust-to-weight ratio propulsion system for landing; lightweight composite structure elements, and a thermal radiator plus heat pipe thermal control system designed to handle the challenging thermal environment on the lunar surface.

The lander's avionics computer is based on a LEON processor card incorporating 8 Gbit of memory for data storage, which will be packaged together with power distribution and interface boards, enabling a low-mass and low-power solution crucial to achieving a small lander configuration. The proposed mission consists of four landers operating simultaneously on the lunar surface. The spacecraft are launched simultaneously on a single Atlas V Evolved Expendable Launch Vehicle (EELV). After the Launch Vehicle performs the trans-lunar injection burn (TLI) the four spacecraft are individually separated from the common launch vehicle adapter. Each spacecraft consists of a liquid propellant lander and a braking stage incorporating a solid rocket motor. Through a series of propulsive Trajectory Correction Maneuvers (TCMs) performed by the lander element each spacecraft is individually targeted to a unique landing site. Following a minimum energy trajectory the spacecraft arrives at the Moon's nearside approximately five days later. A direct descent trajectory is utilized. The braking stages are ignited eliminating the approach velocity. The lander element then separates and performs the terminal landing phase autonomously. Once the lander and instrument systems are deployed and commissioned the science mission begins. The Lunar Geophysical Network operates continuously and concurrently for six years although only the seismometer is required to be in operation at all times. It is critical that seismic events are observed by all four nodes simultaneously. The other instruments benefit from geographic diversity but do not constitute a real time network.

The launch mass of the four spacecraft and their launch vehicle adapter is 3572 kg. On the lunar surface each lander is approximately 200 kg including margins and is approximately 2.3 meters high by 1.5 meters wide. The total payload mass is 27 kg. The full cost of the six-year mission in FY15 dollars is estimated at $903.7 million including reserves.

Scientific Objectives

Science Questions and Objectives

The Moon provides an important window into the early history of the Earth, containing information about planetary composition, magmatic evolution, surface bombardment, and exposure to the space environment. Because the Moon's geologic engine largely shut down long ago, its deep interior reflects its initial composition, differentiation, crustal formation, and subsequent magmatic evolution. Geophysical measurements are often the best, and only, way to obtain information about the composition and structure of the deep lunar crust, mantle, and core. The goal of the Lunar Geophysical Network is to acquire seismic, heat-flow, and magnetic-field data, which will greatly enhance our knowledge of the lunar interior. The major scientific objectives of the Lunar Geophysical Network are:

- Determine the lateral variations in the lunar crust, the structure, mineralogy, composition, and temperature of the upper mantle, nature of the lower mantle, and the size, state, and composition of a lunar core (Seismicity, Heat Flow, Surface Magnetic Measurements, and Laser Ranging).

- Determine the distribution and origin of lunar seismic activity. This includes the distribution, and origin of both shallow and deep moonquakes (Seismicity).

- Determine the global heat flow budget for the Moon in order to better constrain the thermal evolution of our only natural satellite (Seismicity, Heat Flow, Surface Magnetic Measurements, Laser Ranging).

- Determine the bulk composition of the Moon in terms of radioactive heat-producing elements (Seismicity, Heat Flow, Surface Magnetic Measurements, Laser Ranging).

- Determine the nature and the origin of the lunar crustal magnetic field (Surface Magnetic Measurements).

Table 1 provides traceability between the objectives and the science instruments.

Science Objective	Measurement	Instrument(s)	Functional Requirement
A) Determine the internal structure of the Moon	Thickness, composition, temperature, and lateral variability of major internal layers (Crust, mantle, core)	Seismometer, Heat Flow probe, Electromagnetic Sounding, Laser Retroreflector	Seismometers simultaneously operating at 4 widely-separated stations Co-location of other instruments
B) Determine the distribution and origin of lunar seismic activity	Seismic detection of deep and shallow moonquakes	Seismometer	Seismometers simultaneously operating at 4 stations Mission lifetime of 6 years (1 lunar tidal cycle)
C) Determine the global heat flow budget for the Moon	Value and variability of heat flow measurements in major lunar terrains	Heat Flow Probe, Electromagnetic Sounding	Heat flow measurements ≥3 m depth
D) Determine the bulk composition of the Moon	Thickness and composition of major internal layers (Crust, mantle, core)	Seismometer, Heat Flow probe, Electromagnetic Sounding, Laser Retroreflector	Co-location of instruments
E) Determine the nature and the origin of the lunar crustal magnetic field	3-component electric and magnetic field determination	Electromagnetic Sounding	Sensors deployed away from lander body

Table 1: Science Traceability Matrix

High-Level Mission Concept

Overview

The Lunar Geophysical Network mission involves the emplacement of four geophysical nodes at geographically diverse locations on the lunar surface. Each node carries a suite of science instruments that operate in a coordinated fashion to probe the interior structure and composition of the Moon. All the nodes are located on the near side of the Moon to allow for direct communications. They operate continuously and concurrently for six years.

Figure 1 shows the top-level LGN mission concept. The four landers are launched on a single Atlas vehicle from Cape Canaveral, Florida. After ascent, a parking orbit of less than one orbit, and trans-lunar injection, the four landers will separate from their carrier and be targeted to their individual landing sites through a series of trajectory correction maneuvers.

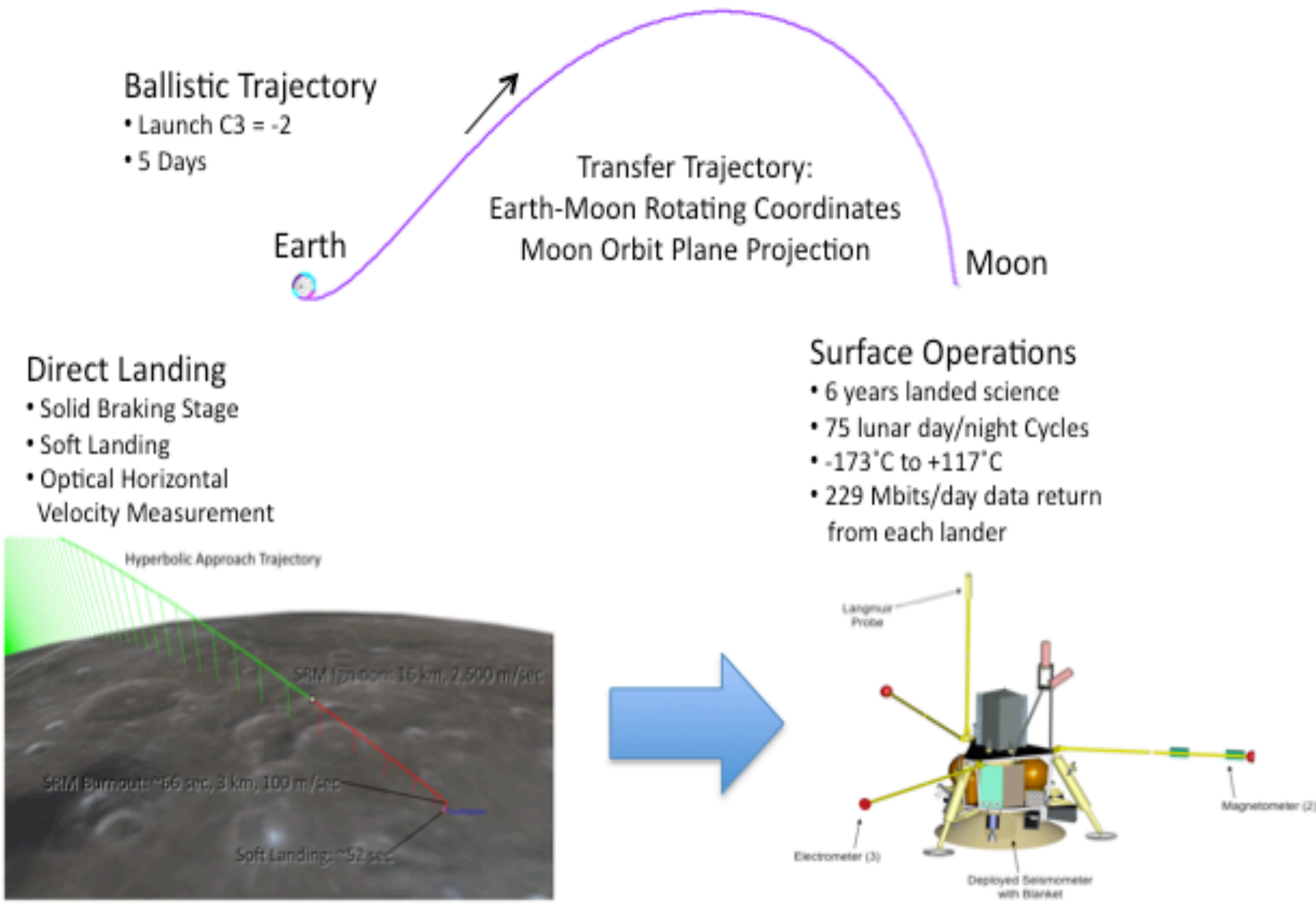


Figure 1: LGN Mission Concept Overview

The trajectory of approximately five days is ballistic, using all chemical propulsion with a direct landing approach at lunar arrival. This mission design reduces complexity and allows use of a solid rocket motor for primary descent braking, maximizing the payload mass to the surface while minimizing total mass. The braking stage will provide the vast majority of the ΔV to land. After completion of the braking burn, the lander will separate from its solid rocket motor and perform a soft landing using onboard liquid hypergolic propulsion. The four landings will occur approximately one hour apart near the time of a full moon. This timing provides lighting that allows optical sensors to assist in vehicle state determination during descent and landing.

Once landed, each lander will deploy a seismometer, three electric field sensors, two magnetometer sensors, a Langmuir probe, and a heat flow sensor mole. A passive retroreflector completes the science instrument suite. After instrument deployment, science operations begin and continue for six years as required to collect seismometry data over one tidal cycle. The electromagnetic sounding and heat flow experiments require data collection for shorter periods of one and two years, respectively. After commissioning, each lander will communicate direct-to-earth using one 4-hour 34 meter DSN track per week.

Several challenges drive the LGN design. Two of these challenges are the direct result of the requirement for a six-year mission, consisting of approximately 75 lunar day/night cycles with surface temperatures ranging from -173˚C to +117˚C.

First, the requirement to operate through the 15.5 day lunar night drives the power system to use an Advanced Stirling Radioisotope Generator. Although an alternate design using solar arrays during daylight and batteries at night could achieve the mission, this approach would stress battery state of the art to survive the long nights over such a long duration, while being heavier, larger, and providing lower power margin than the ASRG approach.

Second, the large surface temperature range challenges the thermal design. During the day, the simultaneous needs to radiate heat from the electronics and to reject heat from the lunar surface present an issue. At night, the need to retain heat to keep the electronics warm is just as large a problem. The lander addresses the daytime heat rejection issue through a parabolic specular reflector / radiator similar to that used by the Apollo Lunar Surface Experiments Package (ALSEP). For nighttime heat rejection, it houses the electronics in a highly insulated Warm Electronics Box (WEB) that maintains internal temperature between -10˚C and +50˚C. In addition, a passively actuated Variable Heat Transfer Link (VHTL) thermally disconnects the electronics from the radiator at night.

Another thermal challenge is the management of the Solid Rocket Motor (SRM) temperatures during cruise and TCMs. The GN&C will execute a 6 rpm rotisserie roll for most of the cruise phase to minimize SRM thermal gradients. However, hot plume impingement from 445N thrusters during TCM burns requires mitigation to prevent the SRM from exceeding its thermal limits. Therefore the SRM is protected by specially designed high temperature multi-layer insulation.

Although the LGN landing accuracy requirements (10 km) are not stressing, the GN&C system must accurately estimate lateral velocity to minimize horizontal rates at touchdown. To do so it uses a Least Squares Optical Flow (LSOF) algorithm. The navigation filter uses inputs from LSOF in addition to a dual head star tracker, IMU, and RADAR altimeter. The LSOF algorithm requires significant processing power, which is provided by a low power and mass LEON-3 based processor.

Custom landing legs must be able to absorb energy and provide stability at touchdown. One option is the use of integral shock absorbers supplemented by crushable honeycomb.

The seismometer must be mechanically isolated from the spacecraft structure to prevent coupling of vibrations that would disturb sensitive seismic measurements, especially from the ASRG and thermal variations. The lander achieves

this isolation through a deployment mechanism that lowers the seismometer to the lunar surface and covers it with an insulating thermal blanket. In addition, the seismometers require relative timing accuracy of less than 5 msec to correlate measurements among the four distributed locations, which is achieved through precise ground-based timekeeping procedures.

The landers include a number of features to minimize mass, including lightweight, high performance Divert Attitude Control System (DACS) descent thrusters developed by DoD. In addition, composite materials are used for the spacecraft decks, the launch vehicle adapter that connects the four landers to the launch vehicle interface, and the Solid Rocket Motor adapter that connects the solid rocket motor to the lander.

Finally, the requirement to develop and execute up to four TCM maneuvers per spacecraft and to execute the direct descents and landings in quick succession presents a challenge to the operations team. As a result, the procedures for TCM design, scripting, and review will be optimized for efficiency, and the landing sequences will be completely automated.

Concept Maturity Level

This study was conducted as a Concept Maturity Level (CML) 5 study (see Appendix B for Concept Maturity Level Definitions). It presents an implementation concept at the subsystem level, as well as science traceability, key technologies, heritage, risks and mitigations. In addition, management partnering and responsibilities are established, and detailed cost models have been developed. Some aspects of CML 6 have been accomplished such as requirements traceability and schedule to subsystem level.

Technology Maturity

Table 2 summarizes the key technologies that have been utilized in the Lunar Geophysical Network mission/lander concept. See Appendix C for definitions of Technology Readiness Levels (TRLs). The table shows the development needed for each key technology, the heritage of the technology, and identifies where risk reduction work is on-going. Technology components considered to be below TRL 6 are addressed in more detail in the Technology Development Plan Section. The required technology advancements noted in Table 2 are believed to be achievable and consistent with the mission schedule outlined in the Development Schedule and Schedule Constraints Section. All other LGN mission components not listed here are evaluated to be TRL 6 or above.

Table 2: Technology Readiness

Technology	Need	TRL	Development Needed	Risk Reduction Activity	Heritage
DoD DACS descent thrusters	Provide high thrust to weight capability	5-6	Extend nozzle and modify valve. Qualify for mission environment. Risk reduction testing to validate thermal performance for LGN mission duty cycle and MON25 combustion stability has been completed. Thermal model correlation in progress.	Yes	DoD
DoD DACS ACS thrusters	High thrust to weight capability	5	Risk reduction testing to validate thermal performance for LGN mission duty cycle and MON25 combustion stability (in progress). Qualify for mission environment.	Yes	DoD
Pressurant Tanks	Custom propellant tank to optimize system mass. Carbon overwrapped aluminum	6-7	Delta qualification for custom sized tank. Low development risk.	No	DoD and other

Propellant Tanks	Custom metal diaphragm tanks to optimize system mass	6-7	Delta qualification for custom sized tank.	No	DoD
Propellant Regulator	High blow down ration for light-weight propulsion system	6-9	Test existing TRL 9 regulator to validate suitability for LGN mission duty cycle and pressure profile (in progress)	Yes	DoD
Advanced Stirling Radioisotope Generator (ASRG)	Power source for 6 year mission duration required for geophysical science objectives	4-6	ASRG being developed and qualified by DoD and Glenn Research Center	NA	Radioisotope Thermal Generator (RTG) missions (e.g., Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
Radiator	Radiator to meet requirements over range of lunar latitudes, potential landing angle offsets, and 6 year exposure to lunar dust and radiation environment	6-7	Demonstrate the feasibility of radiator concept(s) to survive and perform in the lunar environment (thermal, dust, topological, landing attitudes). Provide data for model correlation.	Yes	ALSEP (Apollo), Surveyor, JWST
Thermal Management - variable conductance thermal link	Ability to minimize and maximize WEB heat loss during lunar night but maximize heat rejection during the lunar day	6-7	Development, demonstration, and qualification of a variable conductance thermal link system for LGN application	Yes	DoD, JPL OCO payload, Hubble Space Telescope, Clementine, many others
LEON 3 Processor/SSR	Light weight and low power combined processor and 8 Gbit recorder	4-5	Development of APL LEON3/SSR to TRL 6 (in progress)	Yes	Solar Probe, ESA missions

Key Trades

Table 3 summarizes the key trades that were performed and their results.

Table 3: Summary of Key Trades Performed

Mission Area	Options	Results
Surface Power	• Fuel Cells • Solar/Battery • Small RPS • ASRG	• Fuel cells cannot support a 6-year mission • Solar/Battery can perform baseline mission • Small RPS is, low power margin • ASRG is lower mass, higher power than solar/battery
Launch Vehicle	• Atlas 511 (3915 kg capability) • Atlas 531 (5400 kg capability) • Atlas 551 (6560 kg capability)	• For 4-ASRG lander mission, Atlas 511 provides 11% margin; Atlas 531 provides 57% margin • For 4-Solar/battery mission, Atlas 531 provides 1% margin, or Atlas 551 provides 16% margin
Descent Propulsion	• DoD Divert Attitude Control System (DACS) descent engines • COTS Space Qualified engines	• DACS engines are lighter and smaller • COTS thrusters are still under consideration • Comparison of cost and qualification requirements are still ongoing
Mission Trajectory	• Orbit and Land • Direct Trajectory • Weak Stability Boundary, Libration Point Trajectories	• Direct trajectory is most mass efficient and lowest cost but requires landings ~1 hour apart • WSB and libration point trajectories may be considered

Surface Power and Launch Vehicle

The surface power and launch vehicle trades are closely linked, as the power subsystem is the primary driver for lander mass and volume, and mass and volume in turn drive launch vehicle selection.

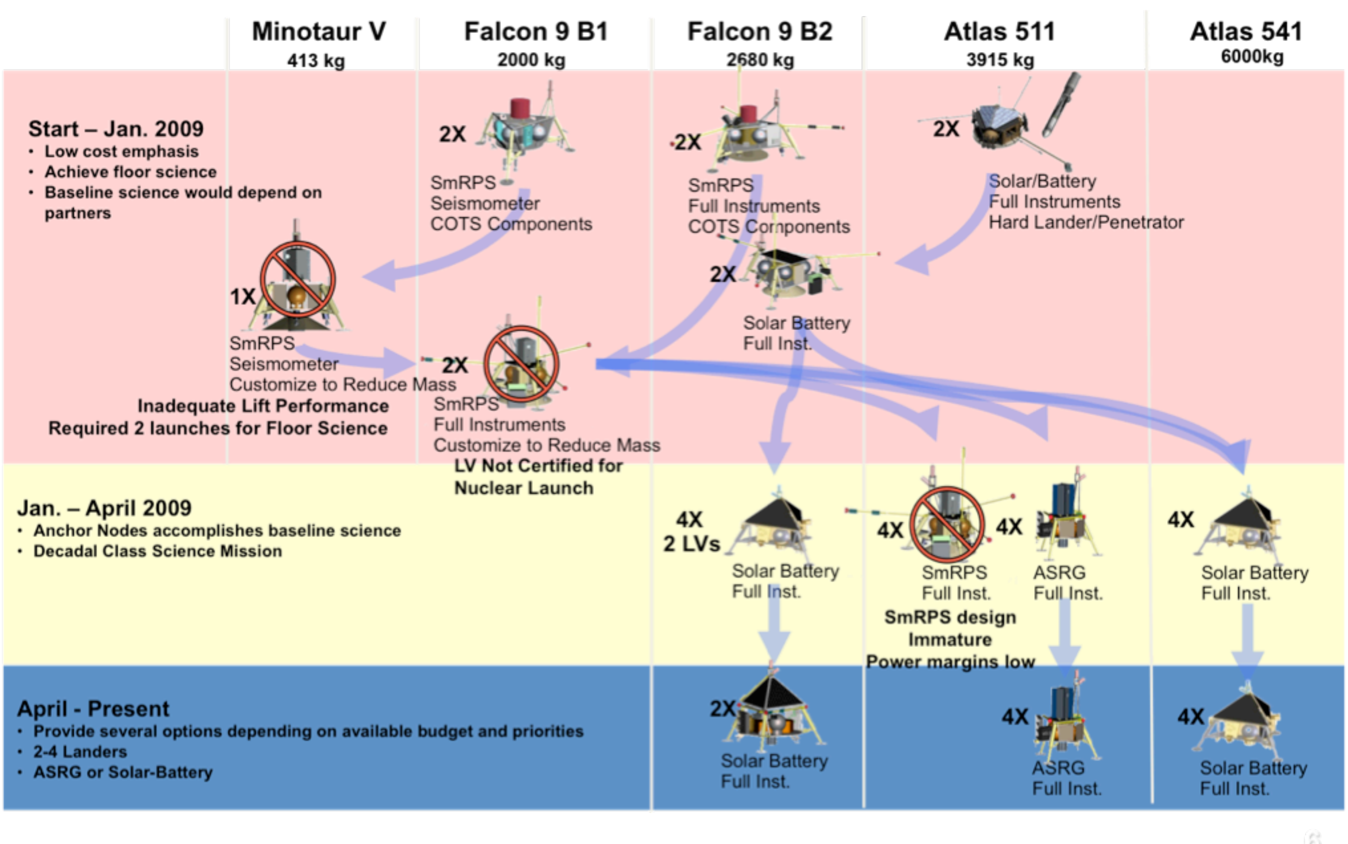
The LGN mission presents significant challenges for the electrical power system. The need to operate for six years at low to mid latitudes imposes a requirement for the lander to survive and operate through approximately 75 lunar day/night cycles, with each cycle consisting of 14 Earth days of light and 15.5 Earth days of darkness.

Two DOE-developed radioisotope power systems were considered: the Small Radioisotope Power System (SmRPS) and the Advanced Radioisotope Stirling Generator. In addition, two non-nuclear power sources were studied: a solar panel / battery combination, and fuel cells.

The nuclear sources provide power continuously with a high power/mass ratio, although they are expensive and require nuclear certification for flight. The ASRG is preferred over the SmRPS because it is more mature and provides more power. Of the non-nuclear options, fuel cells cannot support a six-year mission due to materials technology limitations. The solar battery option can meet the baseline science requirements, but requires a large, heavy battery bank that provides little power margin especially at night, when the science instruments must be cycled to survive until dawn.

Figure 2 shows the evolution of the power source / launch vehicle trade as the LGN architecture concepts have progressed.

Figure 2: Lander Power / Launch Vehicle Concept Evolution



The Atlas V 511 can launch 4 ASRG landers with 11% margin, with the Atlas V 531 as a very viable fallback with 57% mass margin above current estimate with contingency. The Atlas V 531 can launch 4 solar/battery landers with only 1% margin with the Atlas V 551 fallback providing 16% margin. The ASRG lander with fixed landing legs fits comfortably within the 5.4 m fairing, while the solar/battery lander with folding legs has minimal clearance in this large fairing.

Due primarily to power margin, mass, and launch vehicle considerations, the ASRG option is preferred.

Other Trades

Trade studies were also performed in the areas of trajectories, propulsion, and communications.

The direct trajectory approach is currently preferred over low lunar orbit and land and Weak Stability Boundary (WSB) / libration point approaches due to low mass and cost, although WSB/libration point trajectories are a viable option to increase time between landings.

A two-stage solid/bipropellant propulsion system is required to minimize mass. Divert Attitude Control System (DACS) thrusters developed by DoD are currently preferred over COTS thrusters for the liquid stage due to lower mass and size, although COTS thrusters may be lower cost and are still under consideration.

Several relay satellite options were considered, but direct-to-Earth communications are baselined because science objectives can be met with nearside-only nodes.

Technical Overview

Instrument Payload Description

The types of science measurements, corresponding science instruments, and their relationships to overall LGN science goals and objectives have been described in Science Objectives Section of this Report. While instrument operations may affect the timeline due to the overall lander systems design, no science objectives require integrated measurements between the instruments on a particular lander. This study assumed a competed payload. Each instrument is described below.

Seismometer

The seismometer provides 3-axis vector measurement of seismic activity at each LGN spacecraft location in order to characterize lunar background as well as seismic events. All LGN seismometers must operate simultaneously, and to characterize seismic activity over a lunar tidal cycle each seismometer must remain operational for at least six years. The dynamic range of the instrument must be greater than that of the Apollo Passive Seismic Experiment (i.e., ~24 bit), and because of the high sensitivity of requirements, the mission must isolate the seismometer from the vibrational and thermal interferences of the LGN spacecraft. The seismometer's thermal and mechanical stability relative to its surface emplacement must also be maximized.

At some time after an instrument health check, the seismometer will be deployed either below or to the side of the LGN lander (see Flight System section for more detail of deployment methods and hardware mechanisms; deployment mechanism included in mass and cost estimates) to be in full contact with the lunar surface. In order to facilitate interpretation of seismic data across the LGN, each station must have inter-station timing accuracy of ~5 milliseconds, though the nodes do not need to communicate directly with each other.

The seismometer operates continually, generating data to record seismic noise, impact disturbances, and seismic events. Measurement related software is integrated into the instrument package rather than on the lander side of the interface. Ground processing of seismometer data consists of decompression, discrete/engineering unit conversions, and time correlation of data across all LGN nodes.

Table 4: Instrument Table, Seismometry

Item	Value	Units
Seismometer (ExoMars heritage)	1	per Lander
Number of channels	3	axis
Size/dimensions (Sensor)	0.3x0.3x0.3	m x m x m
Size/dimensions (Electronics)	0.2x0.2x0.1	m x m x m
Instrument mass **without** contingency (CBE*)	5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	6.5	Kg
Instrument average payload power **without** contingency	2.6	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	3.4	W
Instrument average science data rate^ **without** contingency	1.6	kbps
Instrument average science data^ rate contingency	30	%
Instrument average science data^ rate **with** contingency	2.1	kbps

*CBE = Current Best Estimate.

^ Instrument data rate defined as science data rate output by the instrument. Compression of seismometry data may reduce overall daily data volume by a factor of 2.

Heat Flow Experiment

The heat flow experiment investigates lunar heat flow by measuring the thermal conductivity and gradients as a function of the depth below the regolith surface. This experiment utilizes a heat flow probe (consisting of a heater and temperature sensor) with a string of ten temperature sensors spaced 30cm apart drawn below the surface behind the heat flow probe. The heat flow experiment may be deployed below the surface using a variety of methods (e.g., penetrator, mole, drill) though for the purposes of this concept study a mole is assumed. The heat flow experiment will be deployed at least 1 meter away from the lander to a depth of 3 meters, and should minimize disturbances to the adjacent regolith and its thermal characteristics. Another challenge is to deploy the assembly such that its thermal conductivity to the surface prevents surface temperature variations, such as those induced by Sun or the lander itself, from being conducted to depth. Finally, there must be a calibrated surface thermal measurement in conjunction with subsurface data collection. The thermal measurements should be made over a minimum 2-year period to monitor propagation of the annual wave and effects of the lunar libration cycle on heat flow and surface heat measurements.

Operations are divided into two phases: penetration, when thermal conductivity is measured by in-situ heating and thermal decay at the approximate final depths of each temperature sensor; and monitoring, when the thermal gradient is measured at each sensor depth. The penetration phase will begin immediately after deployment and consist of a pattern of 0.3m of active penetration (2 hours), a short time of probe heating, and a lunar day of thermal equilibration temperature monitoring before starting the next 0.3m penetration/heating/monitoring cycle. Thus this penetration phase will take approximately 10 months to complete. The monitoring phase will consist of temperature measurements along the thermal sensor column several times a day for a minimum of 2 years thereafter.

Data generation rates and power requirements vary depending on whether the instrument is in active penetration mode or temperature monitoring mode. All measurement software is integrated by the investigation team into the instrument package rather than on the lander side of the interface. Ground processing of heat flow data consists of decompression (if needed), discrete/engineering unit conversions, and analytical adjustment of monitoring data based on thermal conductivity measured during the penetration phase.

Table 5: Instrument Table, Heat Flow

Item	Value	Units
Heat Flow Experiment Package (ExoMars heritage)	1	per Lander
Number of channels	10	sensors
Size/dimensions	0.4x0.4x0.1	m x m x m
Instrument mass **without** contingency (CBE*)	2.5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	3.3	Kg
Instrument average payload power **without** contingency (penetration mode)	10.2	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency (penetration mode)	13.2	W
Instrument average payload power **without** contingency (monitoring mode)	2.3	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency (monitoring mode)	3	W
Instrument average science data rate^ **without** contingency (penetration mode)	0.3	kbps
Instrument average science data^ rate contingency	30	%
Instrument average science data^ rate **with** contingency (penetration mode)	0.39	kbps
Instrument average science data rate^ **without** contingency (monitoring mode)	.001	kbps
Instrument average science data^ rate contingency	30	%
Instrument average science data^ rate **with** contingency (monitoring mode)	0.0013	kbps

*CBE = Current Best Estimate.

** Dimensions & Mass estimates do not include any deployment mechanisms

^Instrument data rate defined as science data rate output by the instrument.

Electromagnetic Sounding

The electromagnetic sounding instrument is designed to determine the electrical conductivity structure of the lunar interior using the magnetotelluric (MT) method of measuring low-frequency electromagnetic induction, and in conjunction with other LGN measurements can help in understanding the global structure and thermal evolution of the Moon. The electromagnetic sounding instrument package will consist of three booms (1.5-2 m in length) deployed from each of the lander legs, horizontal to the lunar surface, each with a magnetometer on the end of the boom. Contact with the lunar surface is not required. In addition, a Langmuir probe will be placed on a mast 0.5m above the highest point on the lander.

After deployment, operations consist of monitoring data from the magnetometer and Langmuir probe and relaying it to Earth. Data should be acquired continually during day, night, and magnetotail passages for a minimum of one year in order assess the different signals and boundary conditions imposed by these environments. Some minor onboard processing and compression may be required prior to storage & downlink.

Table 6: Instrument Table, Electromagnetic Sounding

Item	Value	Units
Electromagnetic Sounding Experiment	1	per Lander
Number of channels (2 Magnetometers, 1 Langmuir probe, 3 electrometers)	3	sensors
Size/dimensions (excluding booms/mass)	.45 x.2 x.2	m x m x m
Magnetometer+Langmuir probe mass **without** contingency (CBE**)	2.6	Kg
Magnetometer+Langmuir probe mass contingency	30	%
Magnetometer+Langmuir probe mass **with** contingency (CBE + Reserve**)	3.4	Kg
Instrument average payload power **without** contingency	4.7	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	6.1	W
Instrument average science data rate^ **without** contingency	1	kbps
Instrument average science data^ rate contingency	30	%
Instrument average science data^ rate **with** contingency	1.3	kbps

*CBE = Current Best Estimate; mass excludes booms, mast, and mechanisms

^Instrument data rate defined as science data rate output by the instrument

Lunar Laser Ranging

Additional lunar laser retroreflectors will increase our ability to measure small irregularities in the lunar rotation due to tidal changes of the Moon's shape and the effects of the lunar mantle and core by laser ranging to the Moon. Each LGN lander will have a laser retroreflector mounted on the lander structure, and the final orientation of the lander will ensure that the retroreflector is within a ±15 degree alignment to the Earth. Materials and structural design of the retroreflectors must minimize the thermal flexing that can introduce measurement error due to photon scattering, and its size and design must result in optical performance to enable a ranging accuracy of less than 2 cm. The retroreflector itself is passive, requiring no power nor generating any data; all data is generated from ground-based laser observations that are not restricted by any lander operational mode or lifetime limitations.

Table 7: Instrument Table, Laser Ranging

Item	Value	Units
Lunar Laser Retroreflector (LRO heritage)	1	per Lander
Number of channels	n/a	
Size/dimensions	0.18x0.16x0.08	m x m x m
Instrument mass **without** contingency (CBE*)	0.9	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	1.2	Kg
Instrument average payload power **without** contingency	n/a	W
Instrument average science data rate^ **without** contingency	n/a	kbps

*CBE = Current Best Estimate.

Table 8: Payload Mass and Power Table

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Seismometer	5	30	6.5	2.6	30	3.4
Heat Flow Experiment	2.5	30	3.3	2.3*	30	3.0
Electromagnetic Sounding	2.6	30	3.4	4.7	30	6.1
Laser Ranging	0.9	30	1.2	n/a	n/a	n/a
Lander Accommodations (blankets, booms, mechanisms)	7.2	30	9.4	n/a	n/a	n/a
Total Payload Mass	18.2	30	23.8	9.6	30	12.5

*Power during penetration mode 10.2W

Flight System

The flight system consists of two main elements: a Star 30 BP solid rocket motor and a lander. A single Atlas launch vehicle launches four identical SRM/lander stacks, with a custom composite Launch Vehicle Adapter providing the structural interface between a standard Atlas adapter and the 4 stacks as shown in Figure 3. A composite Star Motor Adapter provides the interface between the Star 30 BP and the SRM in each of the stacks. The four SRM/lander stacks are deployed shortly after trans-lunar injection by the launch vehicle, after which they perform TCM's to separate to target their individual landing sites.

Figure 3: LGN Flight System – Launch, Cruise and Landed Configurations

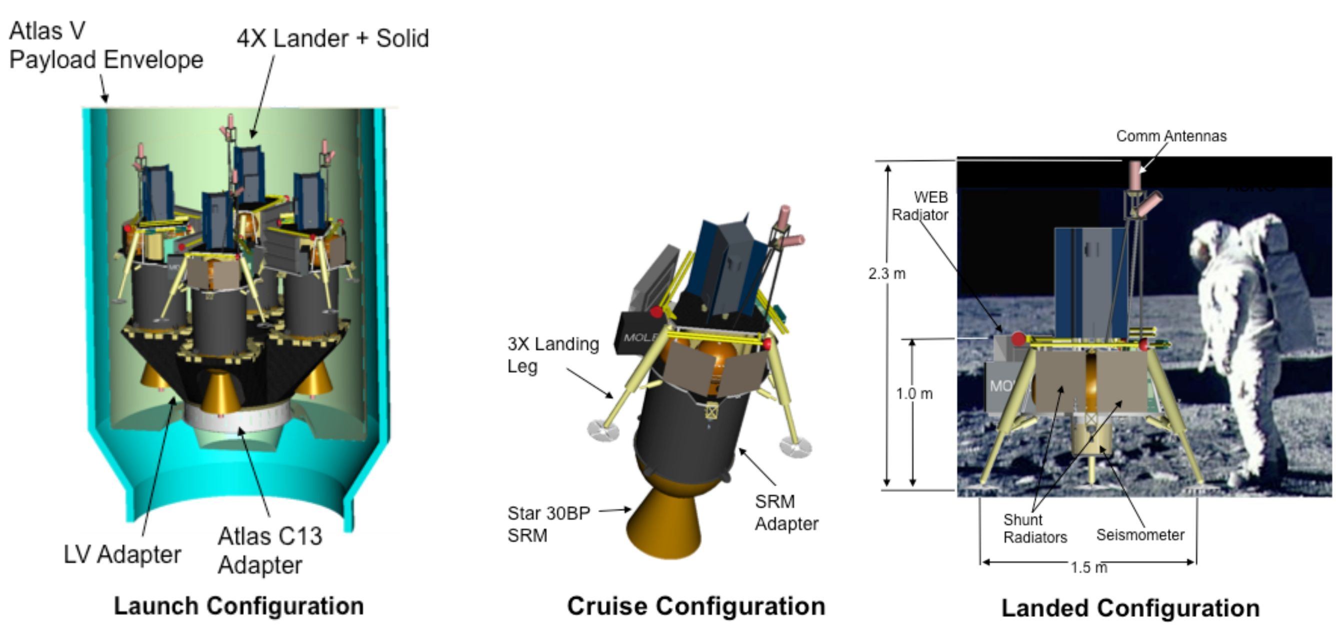


Figure 4 is a block diagram of the flight system, showing the significant subsystems, and Table 9 that follows it shows the lander's mass and power budgets. The LGN ASRG Lander Master Equipment List is found in Appendix E. Table 10 summarizes the characteristics of the flight system.

Figure 4: Flight System Block Diagram of Significant Subsystems

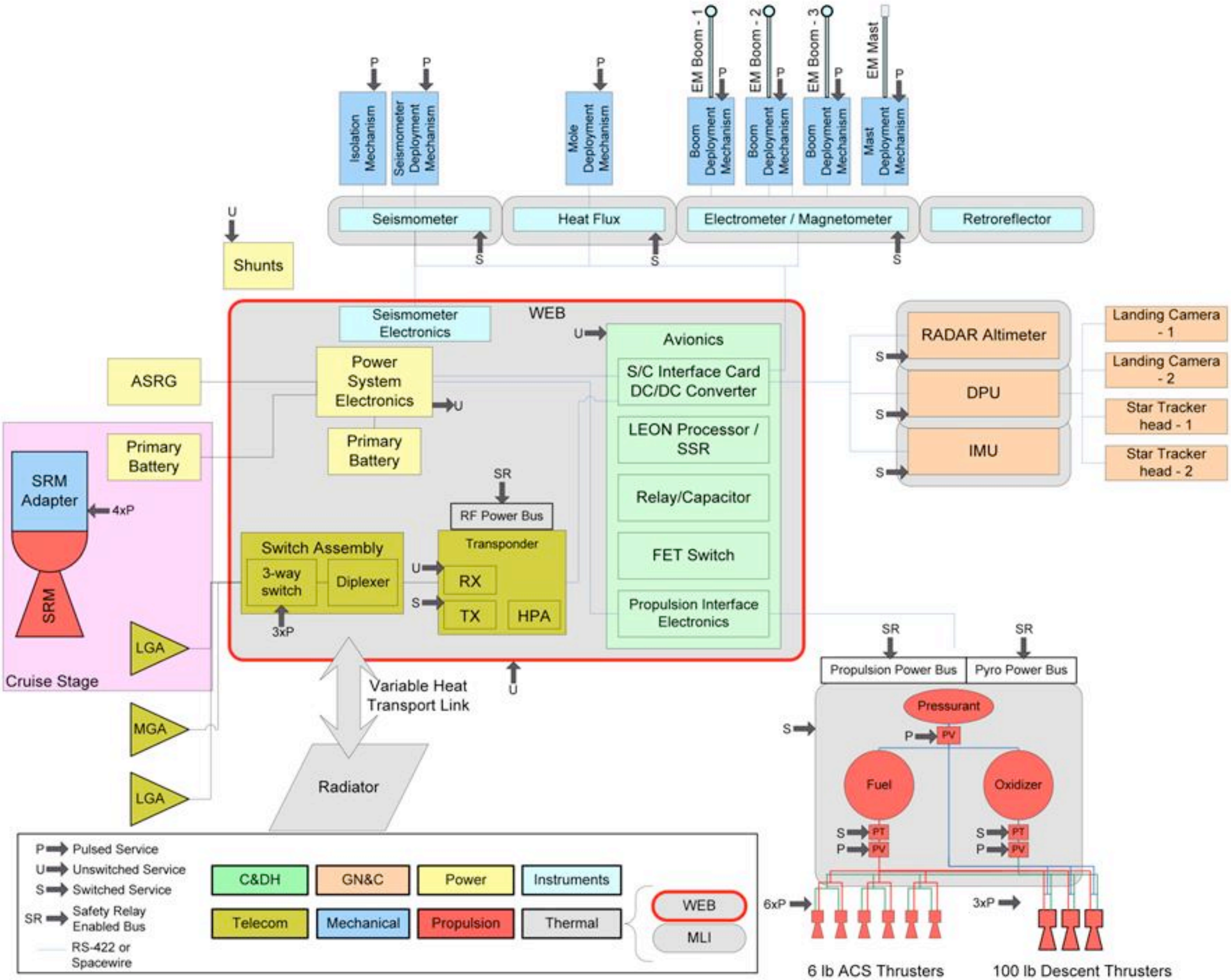


Table 9: Lander's Mass and Power Budgets

	ASRG Lander (kg)		
LGN Lander Subsystems	**CBE Mass (kg)**	**Cont. (%)**	**CBE + Cont. (kg)**
Payload	**23**	**15%**	**26**
Structure & Mechanisms	24	17%	28
Propulsion	26	14%	30
Power	36	14%	41
GN&C	5	10%	5
Avionics	8	15%	9
Telecomm	4	15%	4
Thermal	22	15%	25
Harness	7	30%	10
LANDER			
Lander Dry Mass Total	**154**	16%	**178**
Unallocated System Margin		16%	25
Total Lander System Margin		34%	49
Lander Dry Mass Max Possible			203
Useable Liquid Propellant + Res			54
Lander Wet Mass			**257**
LANDER WITH SOLID			
Star stage Dry Mass	40	30%	52
SRM Adapter, battery + breakup	22	31%	**29**
SRM propellent			**457**
Lander/Solid Wet Mass			**795**
Launch Vehicle Adapter	300	30%	390
Excess Payload capacity			0
Max Estimated launch mass	3211		3572
Launch Vehicle Capability	A V511		**3915**
Launch Vehicle margin		11%	**343**
Launch Vehicle Capability	A V531		**5400**
Launch Vehicle margin		57%	**1828**

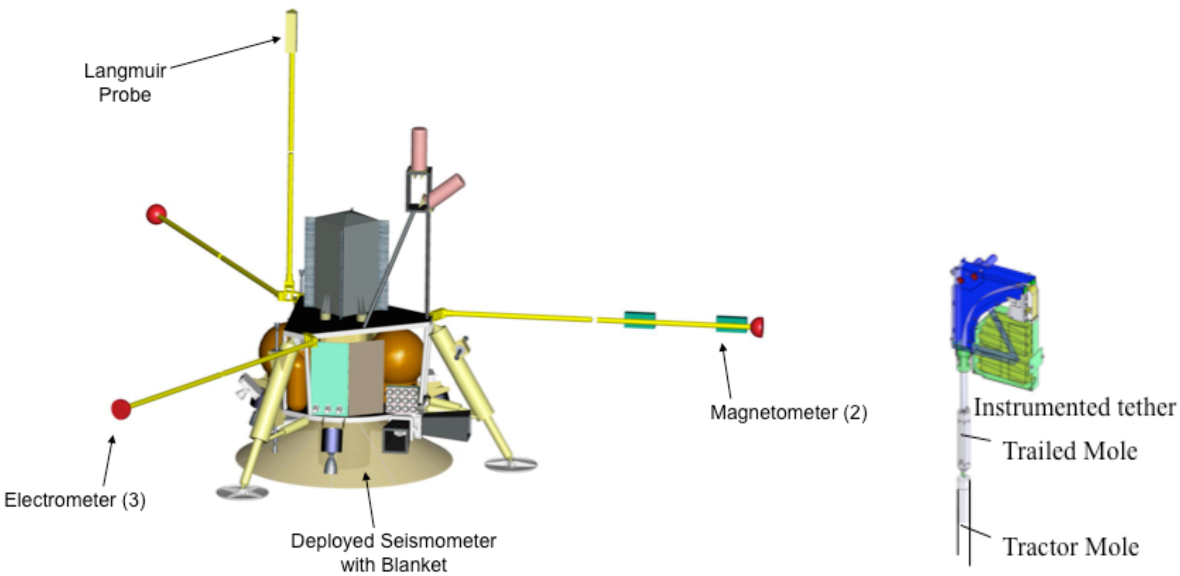
	ASRG Lander (W)			
LGN Lander Subsystems	**Cruise**	**Descent**	**Surface Comm**	**Surface Non-Comm**
Time	**5 days**	**5 min**	**8 hr/day**	**16 hr/day**
Payload	2	2	15	15
Propulsion	3	127	0	0
Power	8	8	8	8
GN&C	16	33	0	0
Avionics	17	17	17	17
Telecomm	8	14	14	2
Thermal	15	0	0	0
Harness	3	10	3	2
LANDER				
Lander CBE Average Power	**72**	**211**	**56**	**44**
Average Power	**72**	**211**	**48**	
Power Contingency	**30%**	**30%**	**30%**	
Total CBE + Contingency (MEV)	**93**	**274**	**62**	
Available ASRG Power	**128**	**128**	**115**	
Available Lander Power (MPV)	**128**	**275**	**115**	
System Margin				
	78%	30%	105%	

Table 10: Characteristics of Flight System

Parameter	**Value**
General	
Design Life	6 years
Structure	
Primary Structure	Composite Upper and Lower Decks, Vertical Struts, Launch Vehicle and SRM Adapters
Landing Legs Structure	3 fixed aluminum legs with honeycomb to absorb energy
Braking Stage to Lander Separation	4 point pyro separation
Deployed structures	3 booms for electrometers, magnetometers 1 mast for Langmuir probe 1 seismometer support structure 1 heat flow sensor support structure
Flight Software	
Data Recording	229 Mbits/day science + housekeeping
Recorder Organization / Protocol	File System / CFDP playback
GN&C frame rates	50 Hz attitude control, 1 Hz.
Operating System / Middleware	VxWorks / GSFC's Core Flight Executive
Communications	
RF Hardware	1 W S-band transponder, 2 LGA, 1 MGA
Data Rates	2 kbps uplink, 4 kbps cruise, 125 kbps surface
Navigation	Coherent Doppler and ranging
Guidance, Navigation and Control	
Control modes	6 rpm rotisserie during cruise 3-axis during TCMs, braking, descent and landing
Attitude determination	Star trackers – Inertial attitude, IMU - Rates
Surface relative sensing	Radar altimeter – range to surface Optical cameras with LSOF – horizontal velocity
Propulsion	
Braking Engine	Star 30BP Solid Rocket Motor, 290 s Isp
TCM / Descent Engines	100-lbf DACS thrusters, MON-25/MMH, 300 s Isp 8.9 Nsec minimum impulse bit
ACS Engines	12 27N DACS thrusters, MON-25/MMH, 270 s Isp 0.53 Nsec minimum impulse bit
Propellant Tanks	1 each - MON-25 fuel, MMH oxidizer, Helium pressurant
Avionics	
Processor	LEON3FT, 60 MIPS @ 75 MHz.
Data Storage	8 Gbits SDRAM with EDAC
Radiation Tolerance	25 KRad TID, SEU tolerant
Power	
Primary Power	ASRG 144 W EOL (day), 122.5 W EOL (night)
Power Management	Linear shunt regulator, Power System Electronics, Power Distribution Unit
Battery	2.3 Ah LiFePO4 primary (cruise)
Thermal	
Thermal Management	MLI, Specular Radiator/Reflector, Variable Heat Transfer Link, thermally insulated Warm Electronics Box, Heaters
Lunar Surface Temperatures	-173˚C to +117˚C
Avionics	-10˚C to +50˚C
SRM	+5˚C to +38˚C storage, +5˚C to +32˚C operating

The lander primary structure consists of two composite decks separated by composite struts. It is supported by three fixed aluminum landing legs with damping shock absorption supplemented by crushable honeycomb to dissipate additional energy. This structure supports the propulsion tanks and all electronics for the lander and instruments. Figure 5 shows the lander's accommodations for the science instruments.

Figure 5: Accommodations for Science Instruments



For seismometer deployment, the lander activates a mechanism that lowers the instrument from its stowed, blanketed position in a shroud attached to the lower deck. Partial lowering allows deployment of spring-loaded arms that unfold the ~1m diameter seismometer thermal blanket. Upon completion of deployment, the seismometer rests firmly on the lunar surface, free of the lander structure, but connected by a cable harness and shaded by its deployed thermal blanket. This arrangement provides power and data communications to the seismometer, and thermal and mechanical isolation from the lander to allow it to make its sensitive seismic measurements.

The lander releases three horizontal booms and one vertical mast to deploy the electromagnetic sounding instrument. Each horizontal boom extends from one of the three lander legs; each has an electric field sensor at its tip, and one of them has two magnetometers inboard of its electric field sensor. The mast extends above the communications antennas to hold the Langmuir probe. Electronics providing power and data communications are attached to the spacecraft structure.

During deployment of the heat flow experiment's mole, the lander holds the instrument box upright. The instrument then performs its own deployment, paying out its instrumented tether and making measurements as the mole descends to a depth of 3 m.

The lander simply provides structural support for the laser ranging experiment's passive retroreflector, which draws no power and has no thermal constraints.

The lander's C&DH and GN&C flight software both execute on a single LEON3 processor. The C&DH software implements a file system on the recorder and uses the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol to ensure 100% file data return. The flight software is built on the Core Flight Executive (cFE) message passing framework, developed by the Goddard Space Flight Center, running on the VxWorks real time operating system.

The S-Band communications system uses two Low Gain Antennas (LGAs) during cruise: one mounted on top of the lander, and the other on the SRM nozzle cover; during flight after SRM ignition, only the top LGA is used. A medium gain antenna is used during nominal surface operations, and the top LGA is available for emergency communications. The transmitter radiates 1 W at 4 kbps during cruise and 125 kbps on the surface; uplink is at 2 kbps. The transponder supports coherent Doppler and ranging during cruise.

The GN&C sensors consist of a dual head star tracker, an IMU, a RADAR altimeter, and 2 optical cameras. Between TCMs during cruise, the GN&C system maintains a 6 rpm rotisserie roll rate for thermal stabilization, changing to 3-axis fixed pointing for TCMs. During final approach and landing, it takes images with the optical camera to null lateral motion using a Least Squares Optical Flow (LSOF) frame-to-frame image correlation algorithm.

Propulsion consists of the 35 kN Star 30 BP SRM and a three-tank MON-25/MMH liquid system pressurized by helium, with three 445 N KEW-5 DACS thrusters and twelve 27 N KEW-7 ACS thrusters. The SRM is responsible for the large braking Delta V maneuver that removes most of the lander's horizontal velocity prior to final descent and landing. The SRM is jettisoned after burnout, and the liquid propulsion system provides thrust for TCMs, attitude control, and landing.

The avionics system is based on a low power LEON-3 processor with an 8 Gbit recorder, housed in a common chassis with the Power Distribution Unit. The LEON-3 provides 60 MIPS while performing descent and landing algorithms, but can be run at lower clock speeds to conserve power during surface operations. In addition, it can be reprogrammed to perform other tasks if desired after landing. The recorder is sized to store a data volume of 229 Mbits/day for 15.5 Earth days of lunar night during which communication to Earth is not available.

The power system consists of an ~130 watt ASRG and associated Power System Electronics, supplemented by a 2.2 Ah Lithium Iron Phosphate battery for propulsion system peak loads during TCM's and descent. After landing, the ASRG provides all electrical power, with 74 W continuously available to the science instruments.

In addition to stabilizing temperatures with the 6 rpm rotisserie roll in cruise, the lander uses high temperature MLI to protect the SRM from hot plume impingement from the liquid propulsion system thrusters during TCMs. On the surface, regolith temperatures range from -173˚C during the 15.5 Earth days of darkness, to 117˚C during the 14 Earth days of light. To protect critical electronic components, the lander houses them in a thermally isolated Warm Electronics Box (WEB) that maintains internal temperatures between -10˚C and +50˚C. During the day, a Variable Heat Transfer Link closes to create a thermal connection between the WEB and a compound specular shield reflector/radiator similar to that used on the Apollo Lunar Surface Experiment Package (ALSEP). During the night, the Link opens to isolate the WEB from the radiator to conserve heat within the box. Science instruments are isolated from the lander and thermally are self-sufficient.

Table 11 lists the heritage for key flight technologies included in the LGN baseline design.

Table 11: Heritage of Key Technologies

Implementation	Heritage
DACS Thrusters	DoD
Radiator	ALSEP (Apollo lunar)
Batteries	Geo communication satellites (many)
LEON3 Processor	Solar Probe

Power Distribution Unit	RBSP PDU
Power Switching Electronics	RBSP, New Horizons, STEREO
RADAR Altimeter	Mars MER and Phoenix landers
GNC Algorithms	ALHAT, MESSENGER, Mars

Concept of Operations and Mission Design

Mission Overview

The LGN mission will launch four nuclear powered landers on a single Atlas launch vehicle from Cape Canaveral, Florida on a direct insertion to the moon. An Atlas launch vehicle is required due to its certification to launch nuclear powered payloads. The launch window is driven by the requirement for illuminated landings. This scenario results in a launch that can occur any month but the specific time of month and window duration (a few minutes per day) will be driven by the arrival lighting constraint. Following the trans-lunar injection burn, the four landers will deploy from the payload adapter and proceed independently on a minimum energy, five-day cruise, directly to the lunar surface. As such, each spacecraft will have to be commanded, tracked, and analyzed as a separate entity. During the five-day cruise period to the Moon, there will be up to four Trajectory Correction Maneuvers (TCMs) planned by the mission operations team for each lander:

Trajectory Correction Maneuver-1

- Directs vehicle to designated landing site
- 6-24 hours post injection
- Adjust for launch dispersions

Trajectory Correction Maneuvers 2-4

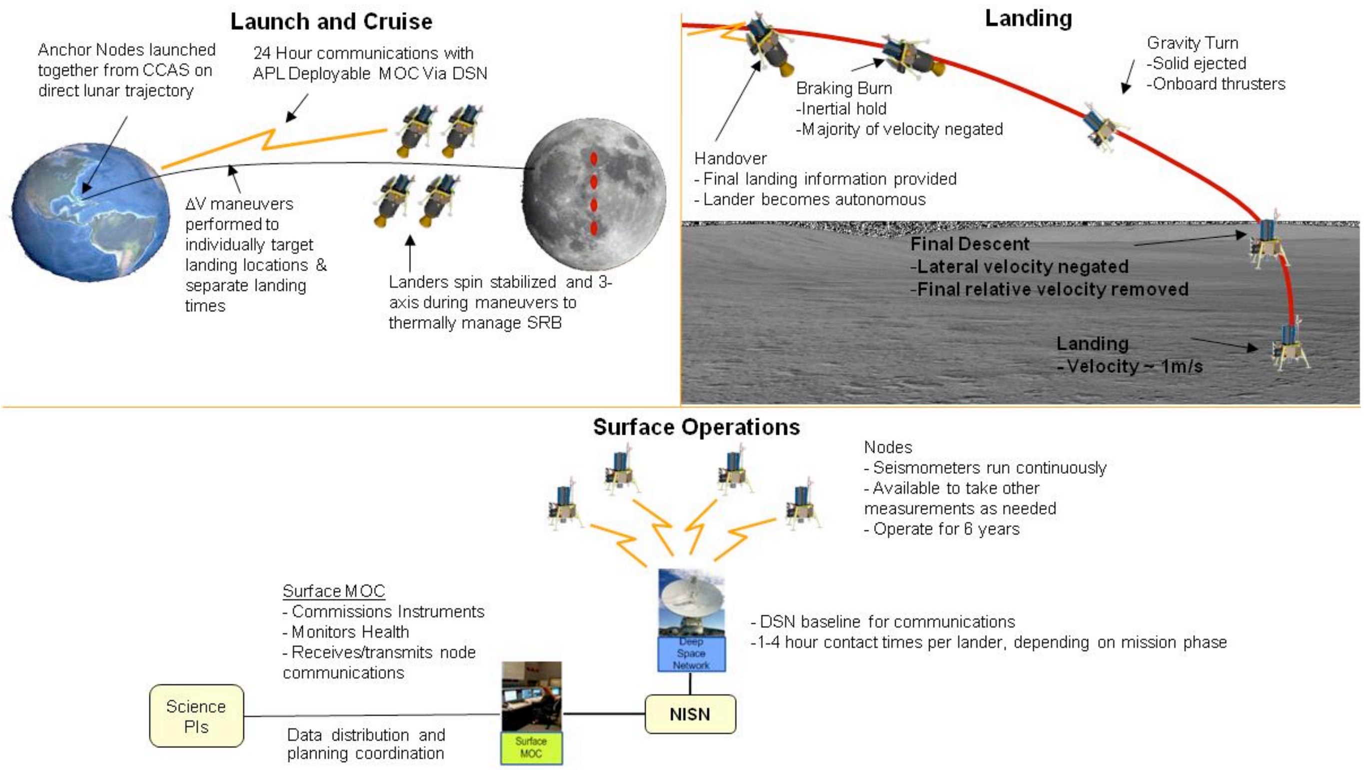
- Adjust trajectory for navigation uncertainties (maneuver performance and orbit estimation)
- TCM-1+1 day to Arrival-1 day

The landing sequences for each spacecraft will be automated. Thus, once initiated, the ground cannot intervene. All four spacecraft are planned to land on the near-side of the Moon with each landing separated by approximately one hour:

Descent and Landing

- Direct to surface (no orbital phase)
- Launch + 5 days
- SRM Braking Burn ~66 seconds
- Final Descent ~52 seconds

Figure 6: Mission Overview



Following a five-day post-landing checkout and twenty day science instrument commissioning, the landers and science instruments will be operated on the lunar surface for six years.

The Deep Space Network (DSN) will be used for all communications (Direct-to-Earth) with the landers throughout the mission. One challenge will be developing a strategy that maximizes two-way communication with the landers during the flight operations phase. For the first ~30 hours of the flight operations phase, all four landers will be within the beam-width of a single 34-m antenna. For the next ~30 hours, two landers will be inside the coverage of a single antenna. Current plans are to maintain contact with all four landers as much as possible during the five day cruise using two DSN dishes continuously. Once on the lunar surface, five days of lander checkout will be performed using two DSN dishes continuously. Following completion of the post-landing checkout, instrument commissioning and initial science collection will begin and continue for twenty days. Throughout this period, a one hour contact with each lander will be scheduled per day. Nominal science operations will then begin and continue for six years. Throughout this phase, a four-hour contact will be scheduled once per week for each lander.

Mission Operations

The main drivers in the development of the LGN mission operations staffing profile for the flight operations phase are derived from mission design. Because four spacecraft are to be tracked and operated simultaneously, there is a need for a larger mission operations team. Each spacecraft will have its own set of maneuvers, contact requirements, and landing sequence to be planned for and executed. Additionally, all activities on the four vehicles will be occurring within a compressed timeframe (five days). In this scenario, the need for a robust operations team that can handle multiple disciplines of planning, assessment, and real-time activity across all vehicles becomes apparent.

To conduct the launch, cruise, and landing operations phases of the mission, the mission operations team will consist of six spacecraft controllers, two mission planners and one operations lead per shift. Operations support will be round-the-clock in order to plan and execute the spacecraft contacts, TCMs, landings, and post-landing checkout. These positions ensure that each lander has the necessary dedication to complete this phase of the mission successfully. In addition to the real-time team, the mission operations effort will also consist of a Mission Operations Manager and spacecraft subsystem support.

Once on the lunar surface, science operations will be performed for a total of six years. The science instruments do not require real-time interaction by the ground. Rather, command loads will be uplinked to each lander containing individual instrument commands that are time executed. The surface operations team will build the weekly timeline, uplink command loads, downlink and distribute recorded data, and monitor the health and status of each lander.

Because the surface operations phase is six years, operational concepts have to strike a balance between the desire for daily data downlink and minimizing mission costs. Analysis has shown that with the assumed data rate of each lander and instruments (229Mb/day), a four-hour DSN contact every seven days is sufficient to retrieve all stored data for an individual lander. Additionally, since the nature of the lander ground contacts should be routine and repeatable, the surface operations team will also develop the capability of automated lander contacts, or unattended operations, through ground command scripting. The unattended operations should further minimize team size for this phase of LGN operations. The unattended operations strategy will be patterned on previous missions such as TIMED, STEREO, and RBSP. Given these assumptions, six controllers (four performing planning/data assessment and two supporting lander contact periods) will be required to plan and execute surface operations. Once operations become routine and automated contacts is fully implemented, staffing can be reduced to four controllers.

Mission Operations Centers

In order to support the mission needs, the mission operations plan calls for two Mission Operations Centers (MOCs) to be developed: a Deployable MOC and a Surface MOC. Both MOCs will contribute during the mission development phases and will be used to support mission simulations. While these MOCs are separate, they will be developed in parallel using common ground software and system architecture.

The Deployable MOC will initially be integrated to support mission operations development, simulations, and Integration and Test (I&T) of the landers. The need for the deployable MOC is rooted in the integration of I&T and mission operations personnel and the short duration of the flight operations phase of the mission. In order to reduce overall workforce for the multi-lander I&T effort, personnel will be shared between the mission operations team and I&T team. The MOC will be re-deployed to the Kennedy Space Center once the landers are shipped to the launch site where it will support final I&T and the flight operations phase of the mission. It will remain there up to thirty days beyond completion of post-landing checkout and will then be returned to the I&T team.

The Surface MOC will be utilized to operate the landers and instruments for the twenty-day instrument commissioning phase and the six years of surface operations. The Surface MOC only needs to accommodate a small surface operations team plus sustaining engineering, but will need to be in service for at least six years beyond launch. It will interface with the remotely-located instrument science teams allowing for distribution of health and status (H&S) telemetry and raw science data from their instruments as well as coordinating mission planning.

A science data web portal will be used for the distribution of data. The surface operations team will place H&S data and level 0 (raw) science data onto the server and the science teams will in turn place the level 1 (calibrated) science

data onto the server. The Surface MOC will maintain an archive of all level 0 & 1 science data as well as all H&S data. Level 2 & 3 science data will be placed onto the Planetary Data System server by the science teams.

Table 12: Mission Operations and Ground Data Systems Table

Downlink Information	**Mission Phase 1 Flight Ops**	**Mission Phase 2 Post-Landing Checkout**	**Mission Phase 3 Instrument Commissioning**	**Mission Phase 4 Surface Ops**
Number of Contacts per Week	Continuous	Continuous	4/day	4
Number of Days for Mission Phase	5 days	5 days	20 days	312
Downlink Frequency Band, GHz	2.25 GHz [1]	2.25 GHz [1]	2.25 GHz [1]	2.25 GHz
Telemetry Data Rate(s), kbps	4	4	100	100
Transmitting Antenna Type(s) and Gain(s), dBi	S-band, -5	S-band, +8.5	S-band, +8.5	S-band, +8.5
Transmitter peak power, Watts	1	1	1	1
Downlink Receiving Antenna Gain, dBi	54.7	54.7	54.7	54.7
Transmitting Power Amplifier Output, Watts	1	1	1	1
Total Daily Data Volume, (MBytes/day)	43.2 [2]	43.2 [2]	114.5 [3]	114.5 [3]
Uplink Information				
Number of Uplinks per Day	TBD	TBD	4/day	4/week
Uplink Frequency Band, GHz	2.07GHz	2.07 GHz	2.07 GHz	2.07 GHz
Telecommand Data Rate, kbps	2	2	2	2
Receiving Antenna Type(s) and Gain(s), dBi	S-band, -6	S-band, +7	S-band, +7	S-band, +7

Risk List

The risks identified for the LGN mission are discussed below. Figure 7 provides a 5X5 risk matrix that illustrates the current assessment of the relative risk likelihood and consequence. Table 13 lists currently funded risk mitigation activities that are scheduled for completion at in FY10. A brief discussion of each risk area is provided below.

(1) ASRG Fuel Availability

The LGN mission concept summarized in this report utilizes an Advanced Stirling Radioisotope Generator (ASRG) as the power source for each lander. The availability of the fuel for the ASRG General Purpose Heat Source (GPHS) is not firmly established and is beyond the lander team's control. However, current information from the Science Mission Directorate indicates that enough plutonium is available to fuel four ASRG landers, dependent on whether or not other future missions are selected that would draw upon the currently available fuel stock.

Potential Consequence: Sufficient GPHS fuel may not be available to support the mission needs.

(2) Lack of Mission Risk Classification Impact on Redundancy

Depending upon the mission risk classification, typically defined after pre-Phase A, there may be a need to add some level of system redundancy.

Potential Consequence: Additional cost and system mass to accommodate selected system redundancy

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[1] Exact channel frequency is TBD until frequency allocation is performed. Uplink and downlink frequencies listed are at center of band.

[2] 24 hours*60min*60sec*4000 bits/s = 345.6 Mbits between 4 landers = 43.2 Mbytes/ day volume for all four landers.

[3] 229 Mbits/ day/ lander = 916 Mbits/ day = 114.5 Mbytes/ day volume for all four landers.

(3) Soft Landing Guidance, Navigation and Control

The planned landing concept, which will make use of optical cameras and lit landing sites for control of lateral velocities, has not been used for a lunar landing. High fidelity end-to-end simulation, field/drop testing, and testing in a "warm gas" lander test bed are planned to reduce the landing risk.

Potential Consequence: Mission cost and schedule could be impacted to ensure safe landing.

(4) Lander Mechanical Isolation from Lunar Surface

The LGN mission science objectives require delicate seismometer instrument vibration sensitivity. Vibrations from the ASRG reciprocating pistons and any other lander induced motion such as thermal expansion and contraction must be isolated from the seismometer and/or be sufficiently defined such that it can be accounted for in the seismometer data reduction.

Potential Consequence: Additional mass beyond current vibration isolation system allocation or science objectives may be impacted by ASRG and/or lander induced vibration.

(5) High Thrust to Weight Bi-Propellant Thrusters Qualification for LGN Mission

The LGN mission concept summarized in this report uses pulsed, high thrust to weight thrusters. Thrusters of this class have flight heritage in DoD applications but the LGN mission will require longer burn times for TCMs and landing and the use of MON-25 propellant to assist with the propulsion system thermal management. Risk reduction testing has recently been performed over a full LGN mission duty cycle for a DoD flight heritage descent thruster. Test results demonstrated good thermal control and combustion stability with MON-25. Planning for testing of a DoD flight heritage attitude control system thruster is in progress with testing planned for spring 2010.

Potential Consequence: Increased propulsion system mass and cost to accommodate conventional thrusters.

(6) Designing for Lunar Day & Night Thermal Environment

The LGN mission concept requires thermal management for continuous operation over the wide range of environmental extremes for lunar night and day and a potential large range of latitudes. Efforts are underway to assess and refine available thermal management systems for this application

Potential Consequence: Additional thermal system mass to meet full mission objectives.

(7) Landing Multiple Vehicles Over Short Duration

The LGN mission concept assumes four independent landings separated by approximately one hour each. To accomplish this, each lander will be commanded, tracked, and analyzed as a separate entity by individual dedicated landing operations teams integrated together by the operations lead and supporting staff. Landing sequences will be automated.

Potential Consequence: Insufficient time to react between landings if complications occur due to systemic issues

(8) Low Mass and Low Power Avionics Development

The planned low mass and low power lander avionics utilizes a LEON3 processor currently assessed below a TRL 6 for the LGN application. Development activities are in progress to bring the LEON3 processor to TRL 6.

Potential Consequence: Additional lander power and battery mass to accommodate a higher power requirement for current mature TRL processors.

(9) Nuclear Launch Certification

Historically the nuclear launch certification and approval process can take years to complete. The process for certification and approval will need to begin very quickly following mission authority to proceed.

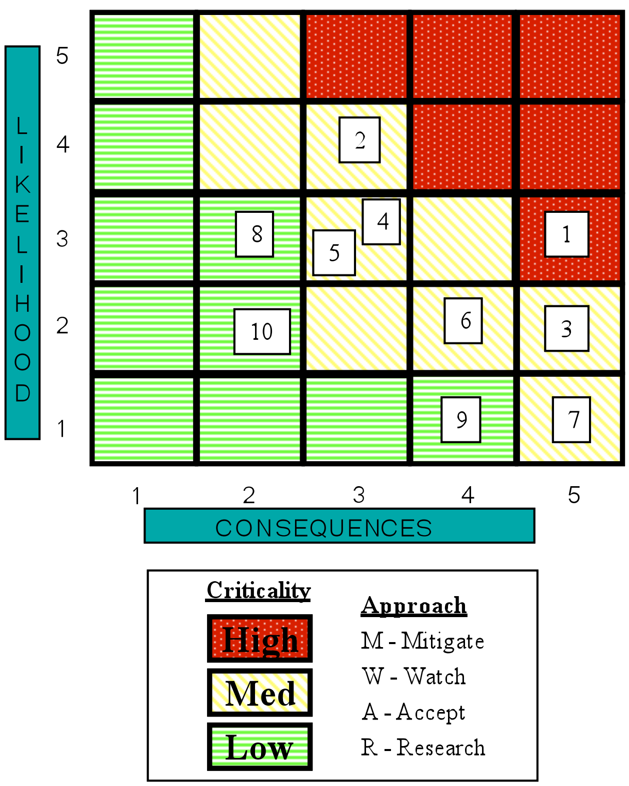
Potential Consequence: Additional schedule time to process nuclear launch certification and approvals.

(10) Helium Pressure Regulator for High Pressure Blow Down Ratio

The LGN mission concept uses a high thrust to weight propellant system that requires a pressurant blow down ratio of up to 10:1. Available high TRL regulators may not be capable of performing as required at a 10:1 blow down ratio. Activities are in progress to test an existing flight heritage pressure regulator to validate its suitability for this application.

Potential Consequence: Additional mass required for the propulsion system to add step regulator if available high TRL regulators are insufficient.

Figure 7: LGN Mission 5X5 Risk Matrix



Impact Key (Primary Impact):
C=Cost; Sc=Schedule; T=Technical; Sf=Safety

Rank	Approach	Risk Title	Impact Type
1	W	ASRG Fuel Availability	T, Sc
2	R	Lack of mission risk classification impact on redundancy	T, C
3	M	Soft landing guidance, navigation & control	T, Sf
4	R	Lander mechanical isolation from lunar surface	T
5	M	High Thrust to Weight Bi-Propellant Thrusters Qualification for LGN Mission	T, C, Sc
6	M	Designing to lunar day and night thermal environments	T
7	M	Landing Multiple Vehicles Over Short Duration	Sf
8	M	Low mass & low power avionics development	T, Sc
9	W	Nuclear Launch Certificaton	Sc
10	M	Helium pressure regulator for high pressure blow down ratio	T, C

Table 13: Risk Mitigation Activities Funded for FY10

Risk # and Description		Technical Solution(s)	Risk Reduction Activities
3	Soft landing guidance, navigation & control	Architecture using Star Tracker, IMU, Altimeter, and Landing Cameras	High fidelity end-to-end simulation HWIL testing, field testing
5	High thrust to weight bi-propellant thrusters qualification for LGN mission	Leverage DoD DACS propulsion technology	Test of DACS thrusters at WSTF in vacuum environment
6	Designing to lunar day and night thermal environment	Thermally isolate electronics (WEB) Diode heat pipe Radiator design based on ALSEP	Develop and test thermal components
8	Low mass and low power avionic development	Develop avionics based on low-power Leon processor	Develop and test Leon processor card
10	Helium pressure regulator for high pressure blow down ratio	10:1 ratio regulator	Testing existing flight heritage regulator in relevant environment

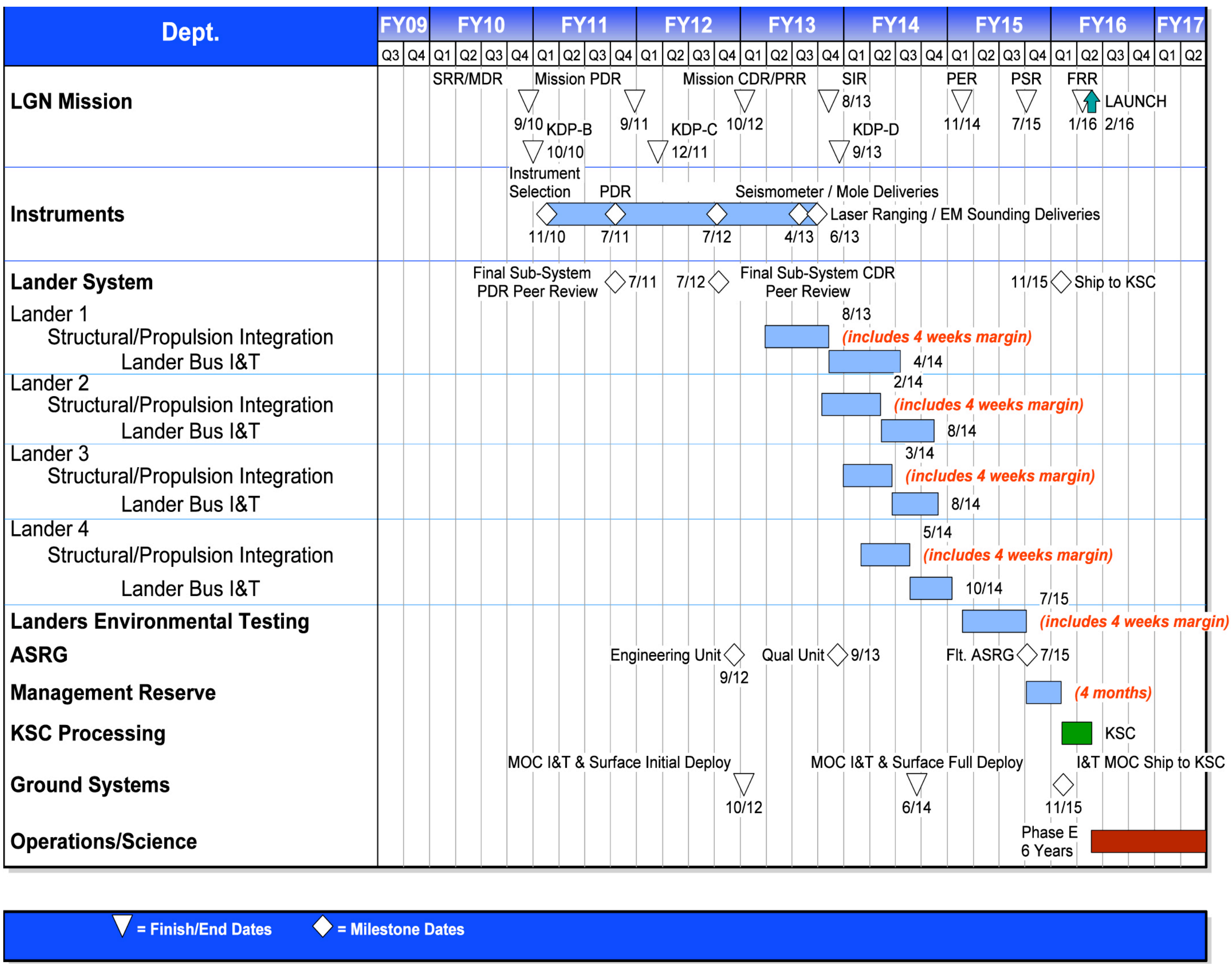
Development Schedule and Schedule Constraints

High-Level Mission Schedule

The key milestone mission level schedule is based on previous mission experience and recent concept development efforts. Key schedule groundrules and assumptions include:

- Lander development and production assumes protoflight approach
- Schedule assumes parallel assembly, integration and test of landers 2-4
- Four months of Project Manager reserves prior to KSC processing
- Additional four weeks reserve on each lander development effort

Figure 8: Four Nodes ASRG LGN Mission Schedule



Key Phase Duration Table

Table 14: Phase Durations

Project Phase	Duration (Months)
Phase B – Preliminary Design	14 months
Phase C – Detailed Design	21 months
Phase D – Integration & Test	29 months
Phase E – Primary Mission Operations	72 months
Start of Phase B to PDR	11 months
Start of Phase B to CDR	24 months
Start of Phase B to Delivery of Instrument #1 and #2	30 months
Start of Phase B to Delivery of Instrument #3 and #4	32 months
Start of Phase B to Delivery of Flight Lander #1	61 months
Start of Phase B to Delivery of Flight Lander #2	61 months
Start of Phase B to Delivery of Flight Lander #3	61 months
Start of Phase B to Delivery of Flight Lander #4	61 months
System Level Integration & Test	7 months
Project Total Funded Schedule Reserve	6 months
Total Development Time Phase B - D	64 months

Technology Development Plan

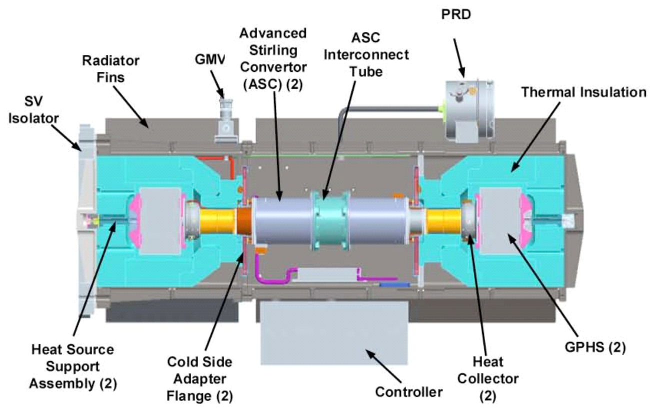
The three lowest TRL key technology elements assessed to be below TRL6 are discussed in this section.

Power

Advanced Stirling Radioisotope Generator (ASRG)

In order to meet the 6-year mission life with continuous operation through lunar day and night, the LGN mission concept summarized in this report utilizes an Advanced Stirling Radioisotope Generator (ASRG). The ASRG, currently in development by Glenn Research Center and the Department of Energy (DoE), makes use of existing General Purpose Heat Source (GPHS) technology used for Radioisotope Thermal Generator (RTG) power sources with extensive space flight heritage (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons). The ASRG incorporates the Stirling energy conversion cycle to significantly increase its thermal energy to electrical power conversion. Stirling convertors have been integrated into an ASRG engineering model with demonstrated efficiency of approximately 28%. While RTGs have an impressive history of providing safe and reliable power for NASA spacecraft, they have a comparatively low thermal to electrical power conversion efficiency of approximately 5 – 7%. Use of the Stirling conversion cycle allows the ASRG to provide ~130 W of electrical power with only two GPHS modules. Use of only two GHS modules compared to eight required for an RTG, drastically reduces the overall mass of the system and also helps better utilize the scarce and valuable Pu-238 isotope.

Figure 9: ASRG Cross-Section

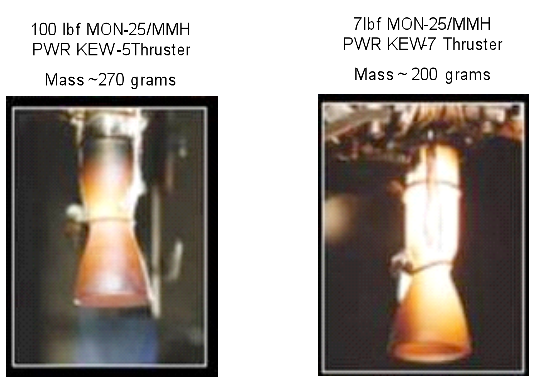


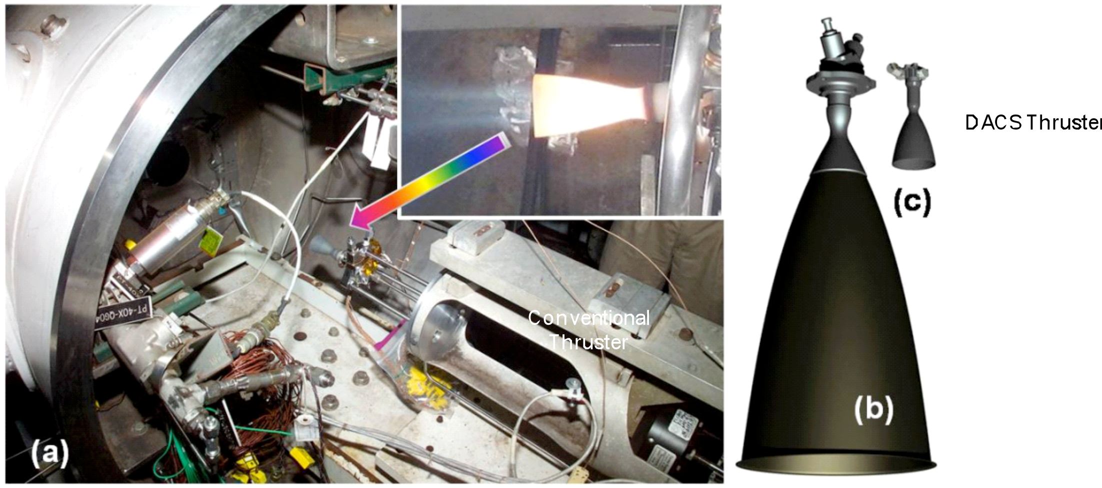
Propulsion

100-lbf KEW-5 (DACS) thruster

The Pratt & Whitney Rocketdyne (PWR) 100-lbf KEW-5 thruster was developed for the Missile Defense Agency (MDA) Divert Attitude Control System (DACS). This thruster could be used as the descent thruster for the LGN mission. Although the DACS thruster has been in operation for many years, the requirements for the MDA application are somewhat different for the LGN mission. The DACS thruster will be required to provide longer duration burns, approximately 60 seconds for the LGN mission, while the thrusters in the current MDA application operate for shorter duration burns right after launch. To enhance the engine performance and reduce the system mass for the LGN mission, the DACS thruster will be used with a cold MON-25/MMH propellant system with low engine inlet pressure. The current DACS thruster uses MON-15/MMH at a relative high engine inlet pressure. Subsequently, the TRL for the thruster is approximately 5 to 6 for the LGN application. Modifications to the thruster valve and nozzle are planned to enhance the performance for the LGN mission. Risk reduction hot-fire testing is in progress to assess the thruster performance and operation in relevant environments. Risk reduction tests already completed on the descent thrusters showed positive results but final thermal and performance data analysis is on-going.

Figure 10: DACS Descent and ACS Thrusters





a) Test Setup in Vacuum Chamber at WSTF for DACS Thruster Hot-Firing and Comparison of Engine Envelope (b) Conventional Thruster and (c) DACS Thruster

Avionics

LEON Single Board Computer/Solid State Recorder

The Single Board Computer (SBC) for the LGN mission concept is based on the Aeroflex LEONFT ASIC (UT699) parc V8 processor. Running at 66MHz the processor performs with 52.6 MIPs. This 6U board also provides a 1GByte Solid State Recorder (SSR). A stacking connector with high speed I/O provides further design capabilities.

Table 15: Features of the SBC Summarized

Processor	Board I/O	Stacking Connector	Stacking Connector
LEON3 Sparc V8 @ 53.6 MIPs	Four 200Mbps Space Wire ports	LEON3FT 16 bit databus access	1 GByte of EDAC protected SDRAM SSR
Low power	Dual CAN bus	Space Wire	16 Mbytes of EDAC protected SRAM
	32bit cPCI	Backplane high speed SERDES	32K x 40 EDAC protected PROM
	Configurable RS422/LVDS console port		Redundant banks of 8 Mbytes EDAC protected EEPROM for code storage
	Configurable RS422/LVDS front panel discretes		Additional 1MByte of EDAC protected EEPROM for FSW use
	10/100 MII Ethernet development interface		
	Front panel accessible debug JTAG and debus Serial port		

As part of on-going risk reduction activities, a prototype version of this board is under development. Development testing to perform all flight control and C&DH functions for the Robotic Lunar Testbed Warm Gas Test Article (WGTA) is scheduled for first flight in August 2010. The WGTA flights will validate the use of the SBC design for flight control applications and pave the way for production of a space qualified version for use on a LGN mission and other space applications.

Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

Ground Rules and Assumptions

Ground rules and assumptions for the LGN estimate are based on the revision 2 draft of “Groundrules for Mission Concept Studies in Support of Planetary Decadal Survey (dGRPDS)”, with exceptions as agreed to by HQ.

Cost estimates are presented in fiscal year 2015 (FY2015) dollars. Initial estimates were generated in spend year dollars and adjusted to FY15 dollars. The inflation adjustment for spend year dollars to FY15 dollars is based on a 2.6% annual inflation rate.

The cost estimates assume that NASA will fund all LGN lander mission costs and that all significant work will be performed in the United States. The mission cost estimates cover activities through the end of Phase E, including the following:

- Project management, systems engineering, and safety and mission assurance
- Science, including science team members
- Instruments
- Spacecraft hardware and flight software development
- Mission operations, including development of ground data systems, DSN charges and Phase E activities
- Launch vehicle and services
- Systems integration and test
- Education/public outreach (E/PO)
- Cost reserves

Per dGRPDS, cost estimates assumed that an ASRG will be ready for flight by March 2014 at a unit cost of approximately $20 million (FY10). The dGRPDS also specified inclusion of a $15 million charge for nuclear launch compliance.

The integration and test WBS covers efforts and expenditures to assemble and check out spacecraft subsystems as well as effort and expenditures to integrate and test the instruments and ASRG.

Launch Vehicle Services Program provided the launch vehicle and services prices for a LGN 2016 launch. In addition to launch vehicle, the WBS 08 element includes costs for the following: composite launch vehicle adapter (LVA), launch vehicle interface engineering, solid rocket motors, including qualification tests, and nuclear launch support and NEPA processing.

Instrument Ground Rules and Assumptions:

- Instrument costs cover the costs of instruments, including mechanisms and booms
- Instruments will be procured via NASA/HQ solicitation:
    - Four instruments per lander
    - Average non-recurring ($7M per instrument) and recurring ($2M per instrument per lander)
    - Operational costs during Phase E included in $1M-per-instrument Science Team cost
    - Independent review found costs “to be conservative and in-family with historic NASA planetary missions”

LGN cost reserve posture is based on the following:

- 30% reserves on Phase B-D costs
- 15% reserves on Phase E costs
- No reserves on E/PO
- No reserves on the launch vehicle and services

Cost Methodologies

This mission concept was independently reviewed by NASA's Office of Program Analysis & Evaluation (PA&E) and was found to be "consistent with the science community definition for a lunar geophysical network" with cost and schedule estimates found to be reasonable and "in-family" with historic NASA planetary missions. This LGN mission concept is technically feasible and the cost estimate is at the upper limit of the New Frontiers range. The full cost of the six-year mission in FY15 dollars is estimated at $903.7 million including reserves and is considered doable for a New Frontiers cost class. The method used to estimate mission costs are summarized in Table 16.

Table 16: LGN Cost Estimating Methodology: Lander Hardware Details

Subsystem	Methodology	Comments
Structures & Mechanical	PRICE-H estimate of composite primary & secondary structural components, aluminum leg structures, balance mass & brackets; associated engineering & technical labor	TRL 6 design effort $120K-per-kg cost comparable to that of MESSENGER, another spacecraft with a composite structure
Propulsion	System design & component qualification tests – analogy to recent and similar level of efforts, with such addition activities as DACS hot test ($6.2M) Thrusters, tanks, valves, other hardware—vendor ROMs Engineering & acquisition labor—bottom-up analysis	Substantial non-recurring costs driven by use of MON-25 propellant, application of high thrust-to-weight DACS thrusters in new context and system-level tests Cost-per-kg significantly higher than that of any recent APL mission
Electrical Power	Battery—build-up analogies to recent MSFC cell costs Power System Electronics/Battery Management Electronics–PRICE-H estimate	Calibrated PRICE-H battery estimate to reflect MSFC data Battery costs cover qualification items & testing PSE, BME based on RBSP slice architecture (single-strand) PRICE-H model calibrated using cost data for RBSP prototype slices All PSE, BME slices—TRL 8 PRICE-H model calibrated using STEREO solar array cost data
Guidance & Control	Components--vendor ROMs, historical price analysis Engineering & technical labor--engineering build up	Use of commercial components (TRL 9) Includes effort for algorithm development

Avionics	Slice design, manufacture & test—PRICE-H Test beds—analogy costs	Reliance on APL slice architecture, reuse of slice design heritage where possible: Leon 3FT slice—TRL 6 by Spring 2010 (risk reduction target) Propulsion I/F slice—TRL 4 Telemetry/Command IF, DC/DC converter slices—TRL 6 FET, capacitor relay slices—TRL 8
RF / Communications	Transponder, diplexer, switches—vendor ROMs Antennas—PRICE-H estimates	Reliance on commercial components (TRL 9) Low cost-per-kg ($230K) compared to historical missions
Thermal*	Custom heat pipe, radiator: vendor ROMs Other materials: historical price analysis Engineering & technical labor: build-up	PRICE-H crosschecks $50K-per-kg cost comparable to those of recent APL missions
Harness (design & fabrication)*	Engineering build-up (as part of I&T scheduling)	PRICE-H crosscheck confirms slight

LGN Total Mission Cost by Fiscal Year NASA Level-2 WBS (In SY$M)

	LGN Mission Costs Phases B-E	9-Mar-10							
NASA WBS	Description	FY11	FY12	FY13	FY14	FY15	FY16	FY17-21	Total
01	Project Management	$ 3	$ 3	$ 3	$ 3	$ 3	$ 1	$ -	$ 17
02	Systems Engineering	$ 3	$ 3	$ 3	$ 4	$ 4	$ 1	$ -	$ 19
03	Safety & Mission Assurance (excl. payload PA)	$ 1	$ 3	$ 4	$ 4	$ 4	$ 1	$ -	$ 17
04	Science/Technology	*	*	*	$ 1	$ 1	*	$ -	$ 2
05	Payloads	$ 4	$ 18	$ 19	$ 8	$ 8	$ 2	$ -	$ 60
06	Spacecraft (4 landers)	$ 56	$ 102	$ 93	$ -	$ -	$ -	$ -	$ 251
07	Mission Operations	$ 1	$ 1	$ 2	$ 5	$ 5	$ 7	$ 38	$ 59
08	Launch Vehicle & Services	$ 5	$ 5	$ 7	$ 80	$ 81	$ 72	$ -	$ 250
09	Ground Data Systems	*	$ 1	$ 2	$ 4	$ 4	$ 1	$ -	$ 11
10	Systems Integration & Test (excl. payloads)	$ 1	$ 3	$ 5	$ 14	$ 14	$ 3	$ -	$ 41
MDA	Mission Design and Analysis	$ 1	$ 1	$ 1	$ 1	$ 1	*	$ -	$ 5
DSN	Space Communications Services (DSN)	$ -	$ -	*	$ 1	$ 1	*	$ -	$ 2
E/PO	E/PO	$ -	$ -	*	$ 1	$ 1	$ 1	$ 5	$ 8
	Subtotal	$ 75	$ 141	$ 139	$126	$127	$ 90	$ 42	$ 741
	Excluding Launch Vehicle	*$ 75*	*$ 141*	*$ 139*	*$ 54*	*$ 55*	*$ 18*	*$ 42*	*$ 525*
	Excluding Payloads, LV	*$ 71*	*$ 123*	*$ 121*	*$ 46*	*$ 46*	*$ 16*	*$ 42*	*$ 465*
	Unallocated Funding Expenditures	$ 19	$ 36	$ 34	$ 12	$ 12	$ 12	$ 11	$ 138
	Total, including Reserves	$ 94	$ 177	$ 174	$139	$139	$102	$ 54	$ 879
	Excluding Launch Vehicle	*$ 94*	*$ 177*	*$ 174*	*$ 67*	*$ 67*	*$ 30*	*$ 54*	*$ 663*
	Excluding Payloads, LV	*$ 90*	*$ 159*	*$ 155*	*$ 58*	*$ 59*	*$ 28*	*$ 54*	*$ 603*

NOTE: Totals are not exact due to rounding.
KEY: *: Less than $1 million

LGN Total Mission Cost by Phase
NASA Level-2 WBS (In SY$M)

NASA WBS	LGN Mission Costs Phases B-E Description	9-Mar-10 Phase B	Phase C	Phase D	Phase E	Phases B-D	Phases B-E
01	Project Management	$ 3	$ 5	$ 8	$ -	$ 17	$ 17
02	Systems Engineering	$ 3	$ 5	$ 10	$ -	$ 19	$ 19
03	Safety & Mission Assurance (excl. payload PA)	$ 2	$ 6	$ 9	$ -	$ 17	$ 17
04	Science/Technology	*	$ 1	$ 1	$ -	$ 2	$ 2
05	Payloads	$ 5	$ 35	$ 20	$ -	$ 60	$ 60
06	Spacecraft (4 landers)	$ 66	$ 186	$ -	$ -	$ 251	$ 251
07	Mission Operations	$ 1	$ 2	$ 13	$ 43	$ 15	$ 59
08	Launch Vehicle & Services	$ 2	$ 12	$ 236	$ -	$ 250	$ 250
09	Ground Data Systems	*	$ 3	$ 9	$ -	$ 11	$ 11
10	Systems Integration & Test (excl. payloads)	$ 1	$ 6	$ 34	$ -	$ 41	$ 41
MDA	Mission Design and Analysis	$ 1	$ 1	$ 3	$ -	$ 5	$ 5
DSN	Space Communications Services (DSN)	$ -	$ -	$ 2	$ -	$ 2	$ 2
E/PO	E/PO	$ -	$ -	$ 2	$ 6	$ 2	$ 8
	Subtotal	**$ 84**	**$ 262**	**$ 347**	**$ 49**	**$ 692**	**$ 741**
	Excluding Launch Vehicle	*$ 84*	*$ 262*	*$ 131*	*$ 49*	*$ 476*	*$ 525*
	Excluding Payloads, LV	*$ 79*	*$ 227*	*$ 111*	*$ 49*	*$ 416*	*$ 465*
	Unallocated Funding Expenditures	$ 24	$ 68	$ 40	$ 6	$ 131	$ 138
	Total, including Reserves	**$ 107**	**$ 330**	**$ 387**	**$ 55**	**$ 824**	**$ 879**
	Excluding Launch Vehicle	*$ 107*	*$ 330*	*$ 171*	*$ 55*	*$ 608*	*$ 663*
	Excluding Payloads, LV	*$ 102*	*$ 295*	*$ 151*	*$ 55*	*$ 548*	*$ 603*

NOTE: Totals are not exact due to rounding.
KEY: *: Less than $1 million

LGN Total Mission Cost
NASA Level-2 WBS (In FY15$M & SY$M)

NASA WBS	LGN Mission Costs Phases B-E Description	9-Mar-10 FY15$M	SY$M
01	Project Management	$ 17.3	$ 16.6
02	Systems Engineering	$ 19.9	$ 19.1
03	Safety & Mission Assurance (excl. payload PA)	$ 17.5	$ 16.5
04	Science/Technology	$ 2.4	$ 2.2
05	Payloads	$ 63.9	$ 60.0
06	Spacecraft (4 landers)	$ 267.0	$ 251.1
07	Mission Operations	$ 53.7	$ 58.7
08	Launch Vehicle & Services	$ 250.2	$ 249.8
09	Ground Data Systems	$ 11.6	$ 11.2
10	Systems Integration & Test (excl. payloads)	$ 40.9	$ 40.8
MDA	Mission Design and Analysis	$ 4.7	$ 4.5
DSN	Space Communications Services (DSN)	$ 2.2	$ 2.2
E/PO	E/PO	$ 7.5	$ 7.6
	Subtotal	**$ 758.7**	**$ 741.0**
	Excluding Launch Vehicle	*$ 542.9*	*$ 525.2*
	Excluding Payloads, LV	*$ 479.1*	*$ 465.2*
	Unallocated Funding Expenditures	$ 145.0	$ 138.0
	Total, including Reserves	**$ 903.7**	**$ 879.0**
	Excluding Launch Vehicle	*$ 687.9*	*$ 663.2*
	Excluding Payloads, LV	*$ 624.0*	*$ 603.2*

Appendices

Appendix A - Acronyms

ACS	Attitude Control System
ALSEP	Apollo Lunar Surface Experiment
ASRG	Advanced Stirling Radioisotope Generator
CBE	Current Best Estimate
CCSDS	Consultative Committee for Space Data Systems
C&DH	Control & Data Handling
CML	Concept Maturity Level
COTS	Commercial off the Shelf
CDR	Critical Design Review
cFE	core Flight Executive
CML	Concept Maturity Level
DACS	Divert Attitude Control System
DoD	Department of Defense
DoE	Department of Energy
DPU	Data Processing Unit
DSN	Deep Space Network
EELV	Evolved Expendable Launch Vehicle
EOL	End of Life
E/PO	Education/Public Outreach
FRR	Flight Readiness Review
GNC	Guidance, Navigation, Control
GPHS	General Purpose Heat Source
GSFC	Goddard Space Flight Center
HPA	High Power Amplifier
H&S	Health & Status
IMU	Inertial Measurement Unit
I&T	Integration & Test
JHU/APL	John Hopkins University/Applied Physics Laboratory
KDP	Key Decision Point
Kg	kilogram
KSC	Kennedy Space Center
LGA	Low Gain Antenna
LGN	Lunar Geophysical Network
LSOF	Least Squares Optical Flow
MDA	Missile Defense Agency
MEL	Master Equipment List
MEV	Maximum Expected Value
MGA	Medium Gain Antenna
MOC	Mission Operation Center
MON	Mixed Oxides of Nitrogen
MSFC	Marshall Space Flight Center
PI	Principal Investigator
PDR	Preliminary Design Review
PER	Preliminary Environmental Review
PRR	Production Readiness Review

PSE	Power System Electronics
PSR	Preliminary Safety Review
PWR	Pratt & Whitney Rocketdyne
RADAR	Radar Detection and Ranging
RLLDP	Robotic Lunar Lander Development Project
rpm	revolutions per minute
RTG	Radioisotope Thermal Generator
RX	Receiver
SBC	Single Board Computer
SIR	System Integration Review
SmRPS	Small Radioisotope Power System
SRM	Solid Rocket Motor
SRR	System Requirements Review
SSR	Solid State Recorder
SY	Spend Year
TCMs	Trajectory Correction Maneuvers
TLIs	Trans-Lunar Injection
TRL	Technology Readiness Level
TX	Transmitter
VHTL	Variable Heat Transfer Link
TRL	Technology Readiness Level
WBS	Work Breakdown Structure
WEB	Warm Electronics Box
WGTA	Warm Gas Test Article
WSB	Weak Stability Boundary

Appendix B – Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Appendix C – Technology Readiness Level (TRL) Definitions

TRL1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a relevant environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

Appendix D – LGN Lander Master Equipment List (MEL)

Nuclear Lander Component/Subsystem	Quantity	Unit CBE Mass (kg)	Total CBE Mass (kg)	Contingency
Structure & Mechanisms			24.35	
Primary Structure	1	4.50	4.50	16%
Secondary Structure	1	3.50	3.50	16%
Landing Leg Assy	3	3.63	10.89	20%
Component Mounting Brackets	1	1.92	1.92	15%
Separation Bracket	6	0.09	0.54	15%
Balance Mass	1	3.00	3.00	10%
Propulsion			25.82	
DACS 100 lbf thruster	3	0.30	0.90	15%
DACS 6 lbf thruster	6	0.09	0.54	15%
Propellant Tank	2	6.50	13.00	15%
Pressurant Tank	1	4.10	4.10	15%
Filters	3	0.15	0.45	10%
Pressure Regulator	1	0.40	0.40	10%
Pyro Valve	3	0.20	0.60	10%
Service Valve	7	0.05	0.35	10%
Pressure Instrumentation	4	0.20	0.80	10%
Temp. Instrumentation	3	0.23	0.68	10%
Lines	1	2.00	2.00	15%
Miscellaneous	1	1.00	1.00	15%
Residual Propellant	1	0.30	0.30	15%
GHe Pressurant	1	0.70	0.70	15%
Power			35.90	
Secondary Battery	0	8.00	0.00	10%
Primary Battery	1	2.50	2.50	10%
ASRG	1	23.50	23.50	15%
Shunt	3	0.47	1.40	5%
PSE	1	8.50	8.50	15%
GN&C			4.65	
Radar Altimeter	1	1.40	1.40	10%
Landing Camera	2	0.30	0.60	10%
Star Trackers	1	1.90	1.90	10%
IMU	1	0.75	0.75	10%
Avionics			7.89	
LEON3/SSR Slice	1	1.49	1.49	15%
SCIF & DC/DC Conv. Slice	1	1.49	1.49	15%
Relay/Cap Slice	1	1.23	1.23	15%
FET Switch	2	1.25	2.50	15%
Inter-Slice Harness	1	0.19	0.19	15%
End Plates	1	0.53	0.53	15%
Fuse Slices	1	0.47	0.47	15%

Telecomm			3.76		4.33
Transponder	1	0.78	0.78	15%	0.90
Antenna	2	0.40	0.80	15%	0.92
Diplexer	1	0.23	0.23	10%	0.25
Switch	1	0.85	0.85	10%	0.94
Cables	5	0.22	1.10	20%	1.32
Thermal			21.55		24.78
Blankets	1	6.90	6.90	15%	7.94
Heaters	1	2.20	2.20	15%	2.53
Diode heat pipe + Radiator	1	5.50	5.50	15%	6.33
Plume shields	1	2.70	2.70	15%	3.11
Tape/Misc	1	2.00	2.00	15%	2.30
Thruster heat sink	3	0.75	2.25	15%	2.59
Harness			7.35		9.55
Harnesses	1	7.35	7.35	30%	9.55
Payload			23.00		26.45
Guest payload	1	5.50	5.50	15%	6.33
EPO Pancam	1	0.30	0.30	15%	0.35
Seismometer	1	5.00	5.00	15%	5.75
Seismometer blanket	1	1.70	1.70	15%	1.96
Seismometer mounting/deployment	1	1.00	1.00	15%	1.15
Mole	1	1.50	1.50	15%	1.73
Mole mounting/deployment	1	1.00	1.00	15%	1.15
EM Sounding	1	2.60	2.60	15%	2.99
Booms	1	3.50	3.50	15%	4.03
Reflectometer	1	0.90	0.90	15%	1.04
Lander Dry Mass			**154.27**	**15.6%**	**178.33**
System Margin				**16.0%**	**24.68**
Useable and Residual Liquid Propellant (useable =			**51.64**		**54.36**
Descent	1				24.67
Braking	1				9.70
TCM	1				19.99
Lander Wet Mass					**257.37**
Star Adapter + Battery			21.98		25.50
Separation Nut	4	0.15	0.60	15%	0.69
Lander Separation Bracket	4	0.27	1.08	15%	1.24
Lander Sep Springs/Switches	1	1.00	1.00	15%	1.15
Star Honeycomb Adapter	1	5.90	5.90	20%	7.08
LV Separation Ring	1	3.90	3.90	15%	4.49
Primary Battery	1	2.50	2.50	12%	2.80
SRM Breakup assy	1	7.00	7.00	15%	8.05
Star custom Assembly			497.20		512.30
Star SRM Dry Mass	1	37.70	37.70	15%	43.36
Star SRM Propellant	1	456.85	456.85	0%	456.85
Solid S&A, destruct	1	2.00	2.00	15%	2.30
Omni Antenna Bracket	1	0.25	0.25	15%	0.29
Omni Antenna	1	0.40	0.40	15%	0.46
Dry System Margin 15%				15%	9.05
Lander plus Solid Total Mass					**795.17**